# Amorphous optical coatings for gravitational-wave interferometers

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LABORATOIRE MATÉRIAUX AVANCÉS

GWADW 2016 – Elba

# outline

motivations

experimental setups

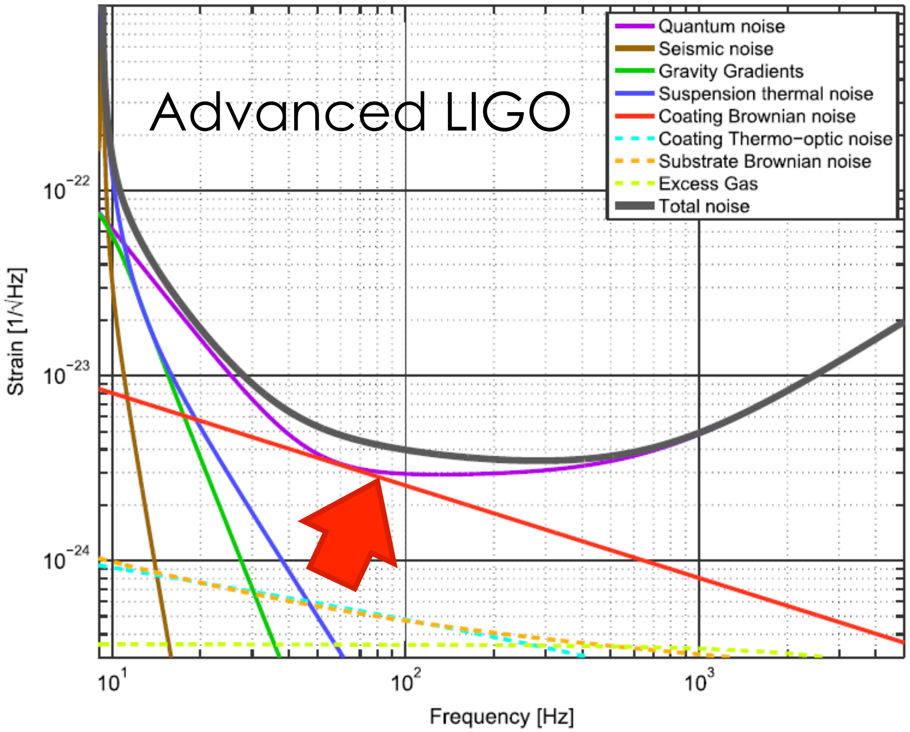
latest results

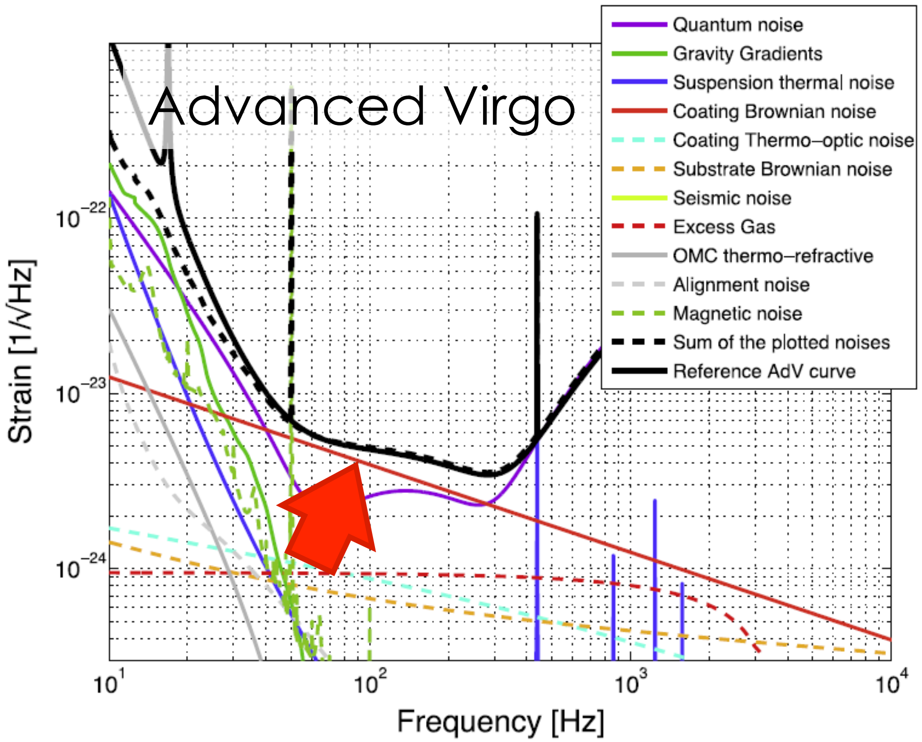
- measured dilution factor
- deposition parameters and annealing
- advanced detectors' coatings
- some new coating materials

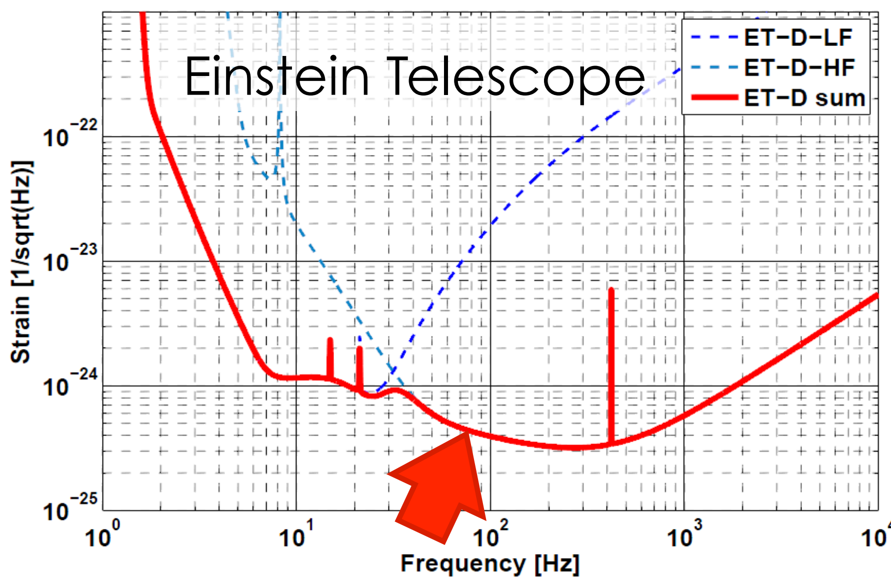
summary and conclusions

# coating thermal noise

issue for present/future detectors




Aasi & al, Class. Quantum Grav. 32 (2015)
Acernese & al, Class. Quantum Grav. 32 (2015)
Abernathy & al, ET-0106C-10 (2011)

# requirements

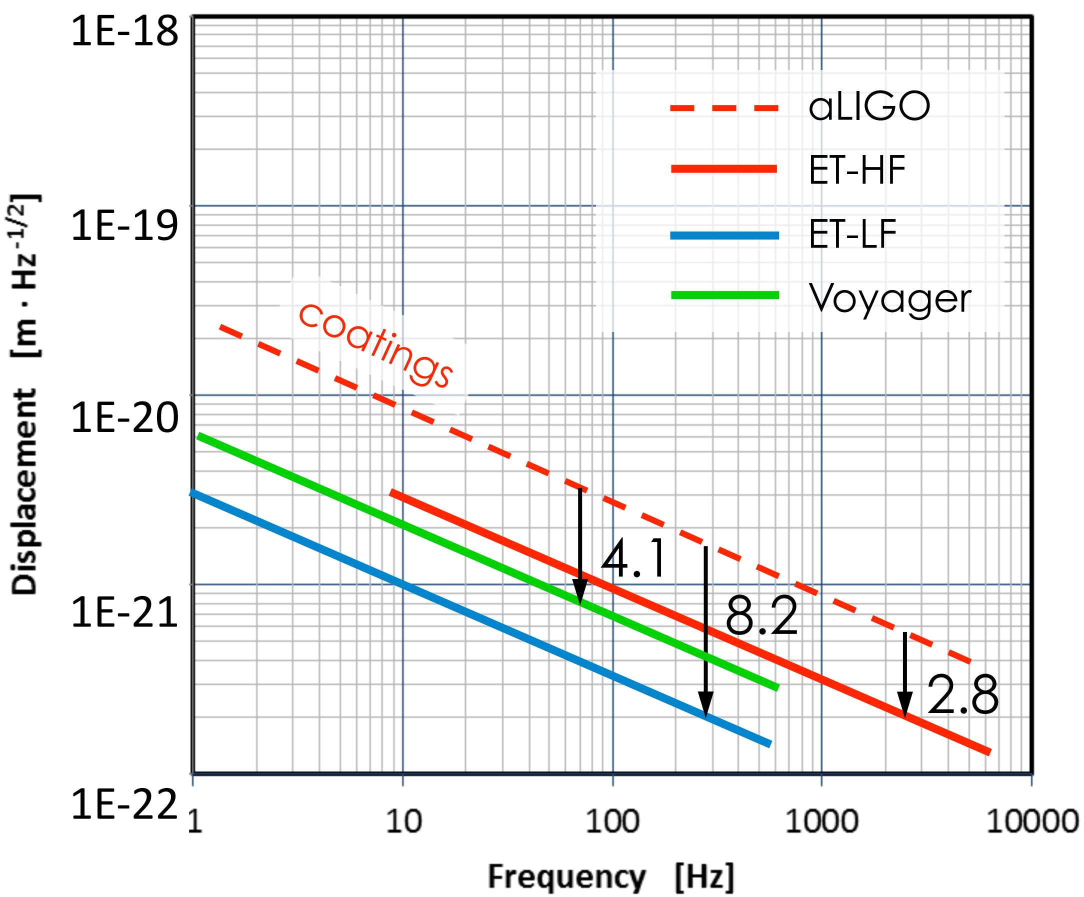
mitigation from:

temperature
beam size/shape
loss angle

ET-HF: $2.8 = 1.7\sqrt{2.7}$

ET-LF: $8.2 = \sqrt{30}\ 1.7\ \sqrt{0.8}$

Voyager: $4.1 = \sqrt{2.4}\ \sqrt{7}$



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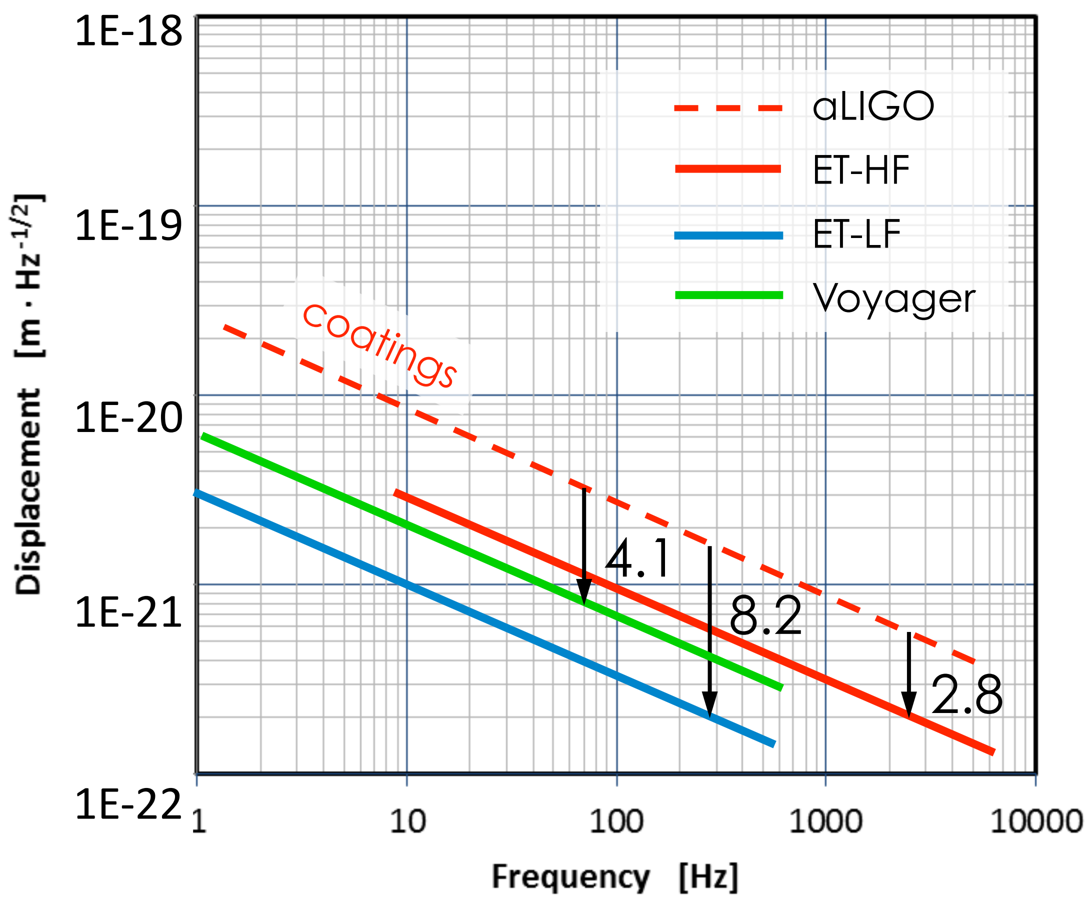



new materials
*and*
thickness uniformity

upgrades of
Advanced LIGO/Virgo

Einstein Telescope
Cosmic Explorer / Voyager

# research & development @ LMA

technological developments

- thickness uniformity over ø 600 mm – ongoing
- in-situ control system – ongoing
  - improved repeatable ARs
  - twin mirrors from simple rotation

new materials

- ambient temperature high-index materials – ongoing
- cryogenic temperature high-index materials – ongoing
- cryogenic temperature low-index materials – starting soon
- sapphire payload (substrate+coatings+suspensions) – in progress

# experimental setups

# ion-beam sputtering (IBS)



*photos: C. Fresillon – photothèque CNRS / E. Le Roux*

# metrology – optics

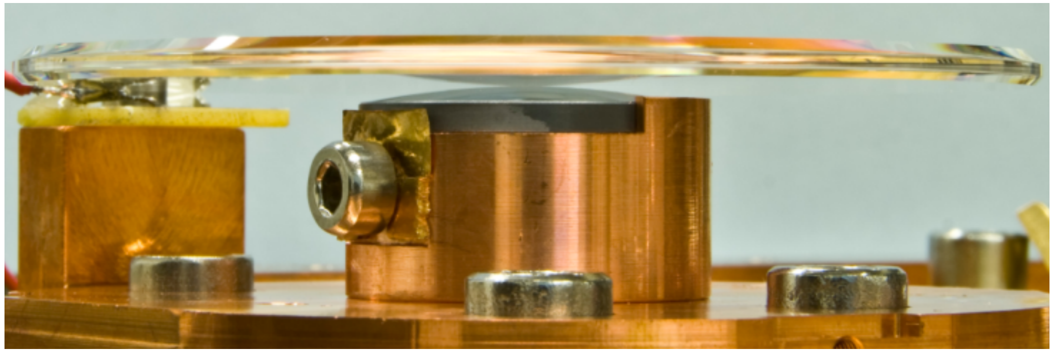
- scattering
- surface defects
- wavefront
- absorption [ambient/cryogenic]

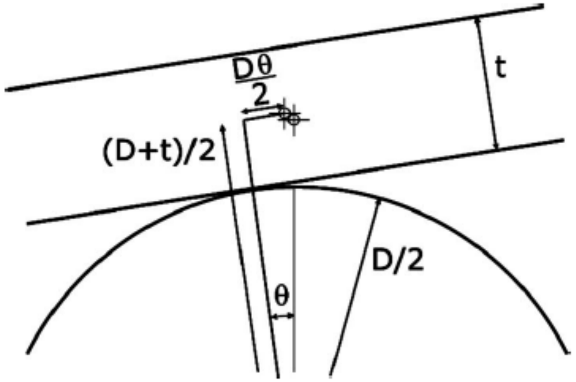



*photos: C. Fresillon – photothèque CNRS*

# metrology – mechanical loss

Gentle Nodal Suspension
(GeNS)

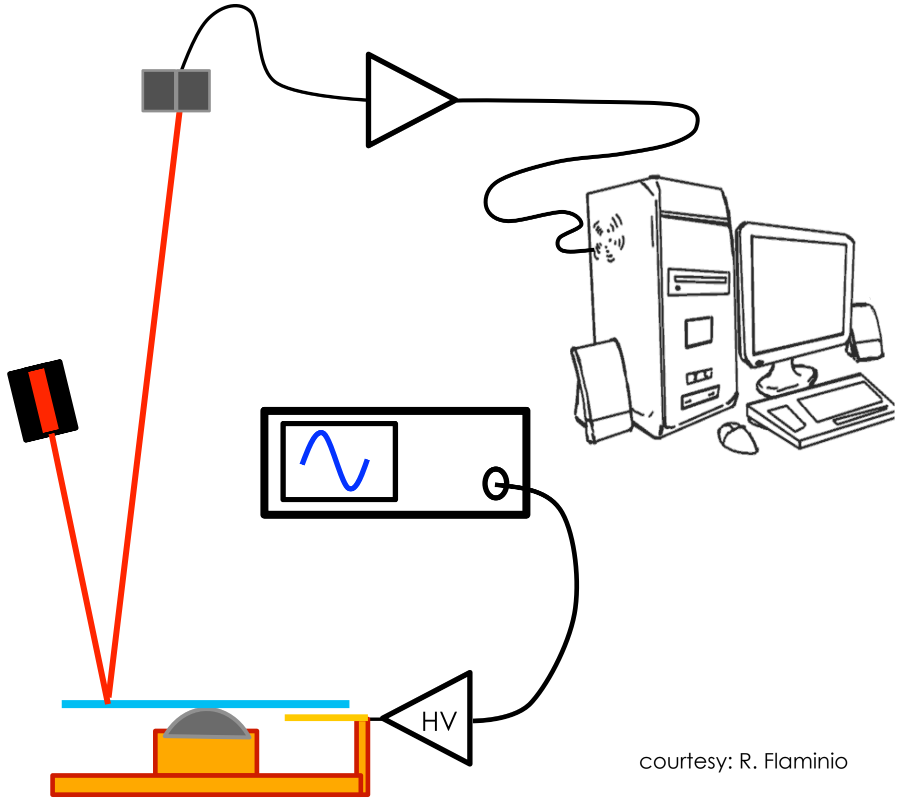





electrostatic excitation

optical lever + qPD readout

LabVIEW-based acquisition software




Cesarini & al, Rev. Sci. Instrum. 80 (2009)
Cesarini & al, Class. Quantum Grav. 27 (2010)

courtesy: R. Flaminio

# LMA coating loss measurement protocol

substrates – SiO2 disks

- optically polished Corning 7980
  d = 3''  t = 1 mm  [flats]
  d = 2''  t = 1 mm  [flats]
- micropolished Corning 7980
  d = 3''  t = 2.5 mm

coatings

- on both surfaces

annealing

- 10 h @ 900° C before coating
- 10 h @ 500° C after coating

# measured dilution factor[*]

[*] Li & al, Phys. Rev. D 89, 092004 (2014)

# dilution factor

coating

measured before coating

$$D = \frac{E_c}{E_{cs}} \simeq 1 - \left(\frac{f_0}{f}\right)^2 \frac{m_0}{m}$$

coated sample

measured after coating

# dilution factor – TiO2Ta2O5 GC

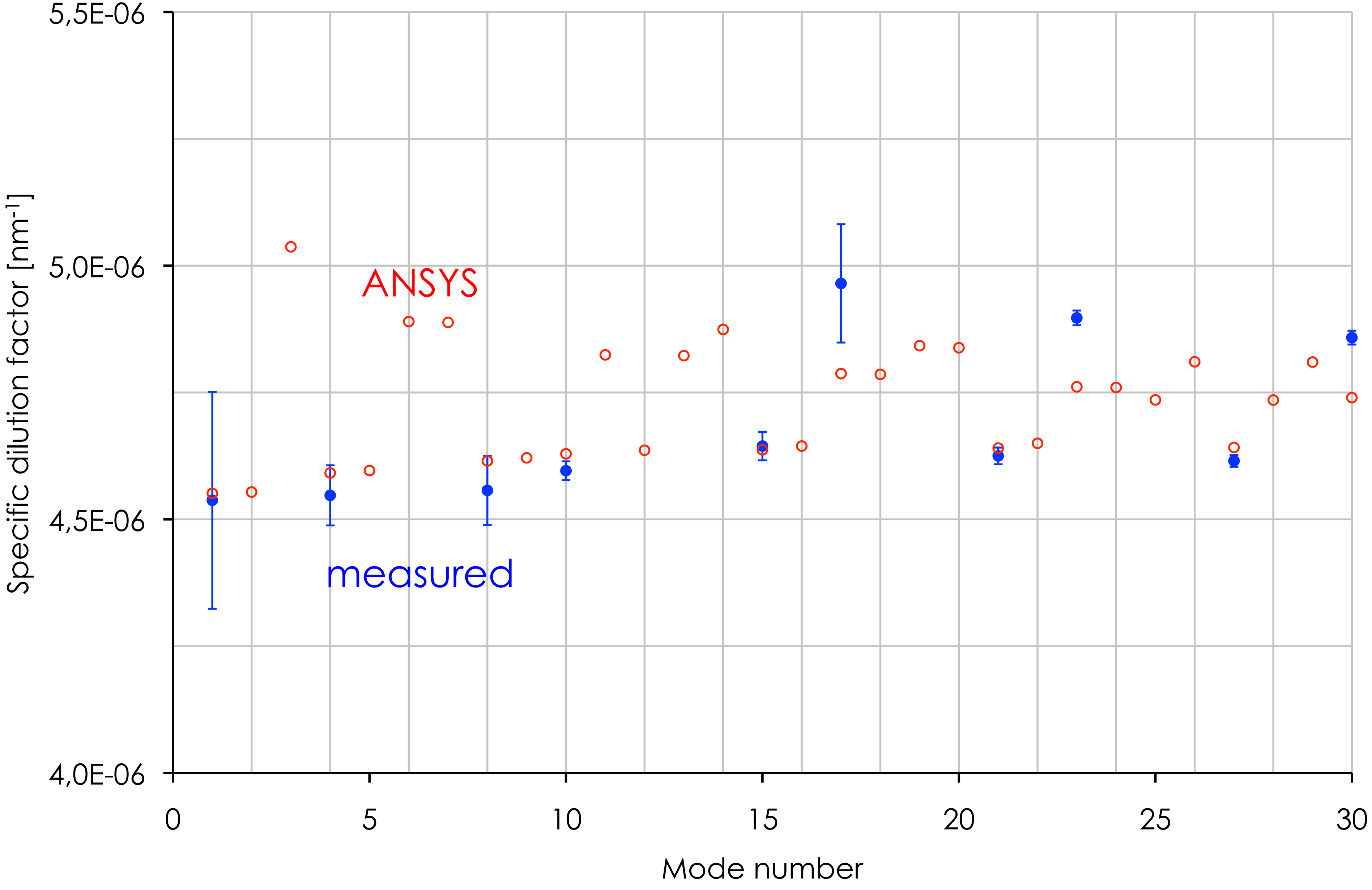
$$D = \frac{E_c}{E_{cs}} \simeq 1 - \left(\frac{f_0}{f}\right)^2 \frac{m_0}{m}$$

ANSYS

$t_s$ = 1.05 mm
$Y_s$ = 72.3 Gpa
$\nu_s$ = 0.164
$\nu_C$ = 0.230
$\rho_s$ = 2200 kg/m$^3$
$\rho_C$ = 6640 kg/m$^3$

measured
[mass / thickness (spectroscopic ellipsometry)]

# *specific* dilution factor – TiO2Ta2O5 GC



# dilution factor – TiO2Ta2O5 GC

estimation of coating Young's modulus:

$$D = \frac{E_c}{E_{cs}} \simeq 1 - \left(\frac{f_0}{f}\right)^2 \frac{m_0}{m}$$

ANSYS

$t_s$ = 1.05 mm
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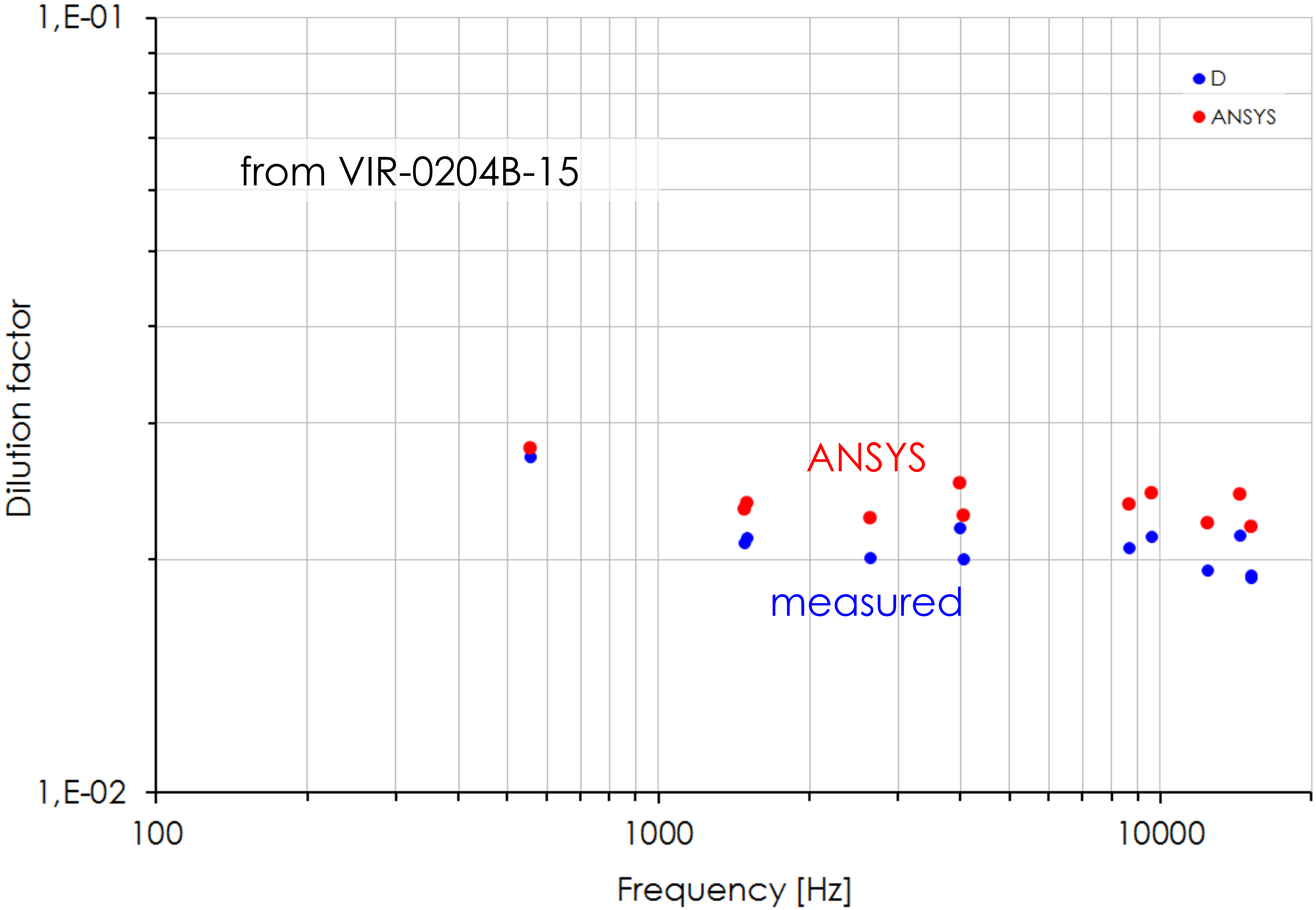
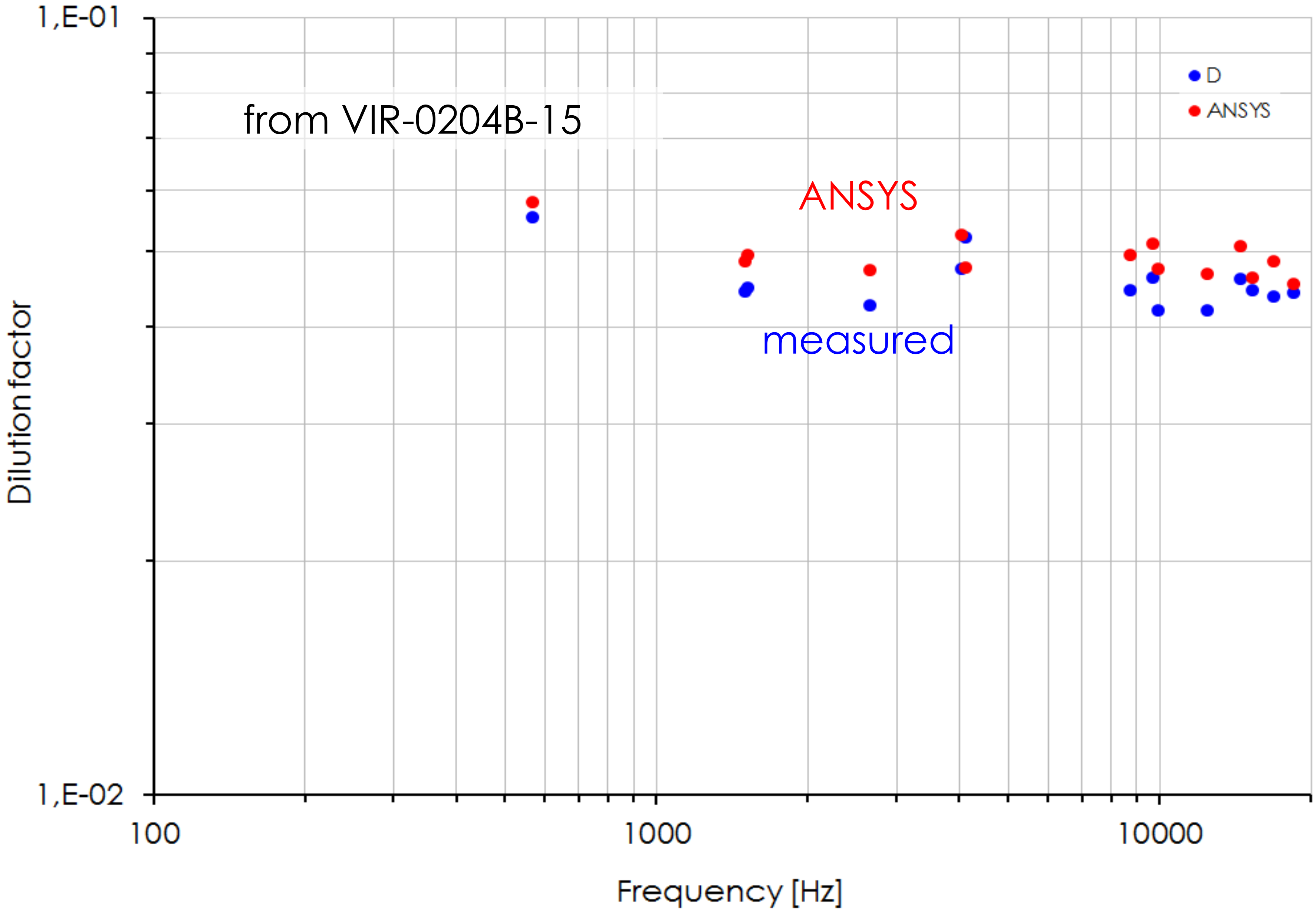
$\rho_s$ = 2200 kg/m$^3$
$\rho_c$ = 6640 kg/m$^3$

$Y_c$ = 122 Gpa

# ITM coating [on Si]

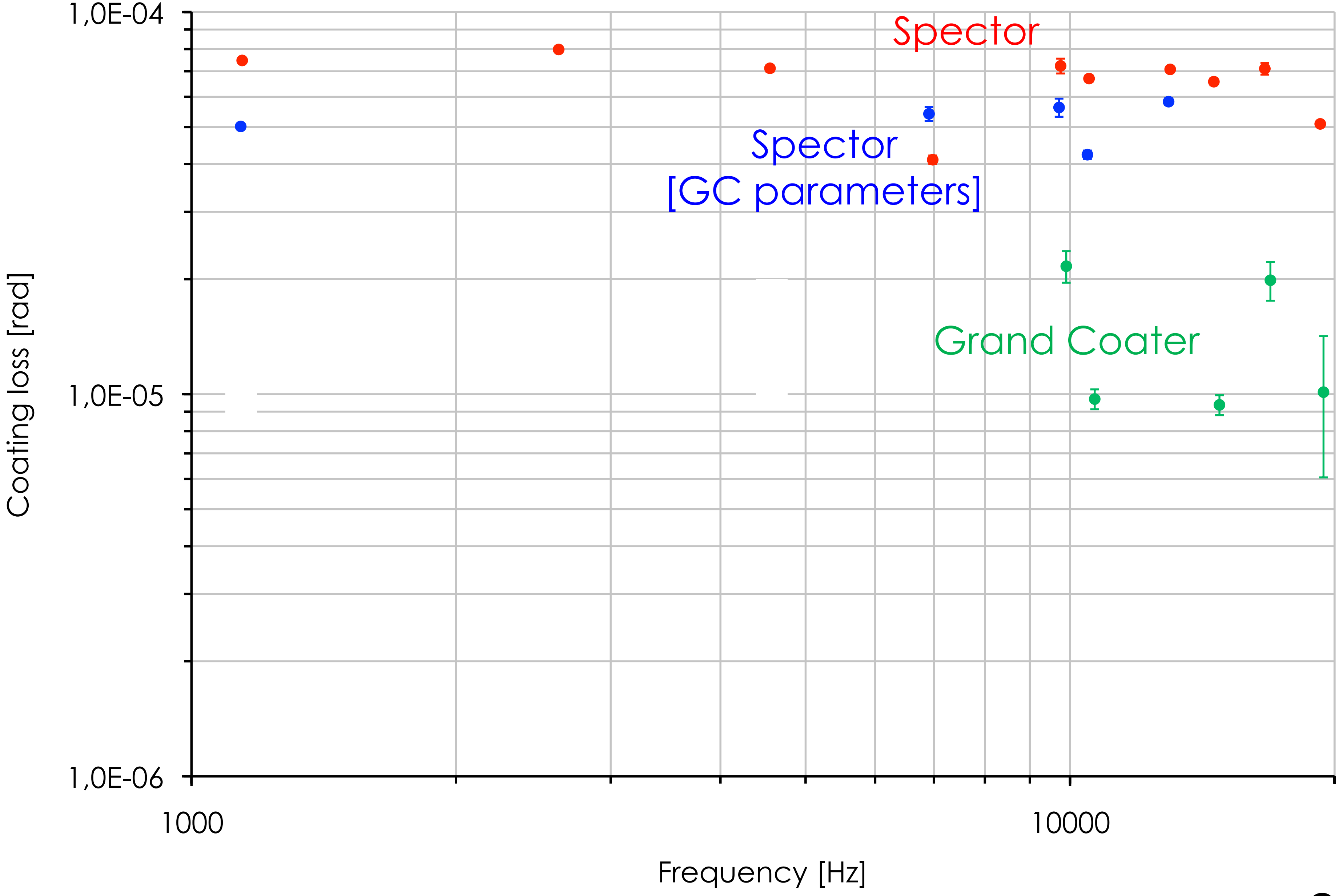


# ETM coating [on Si]

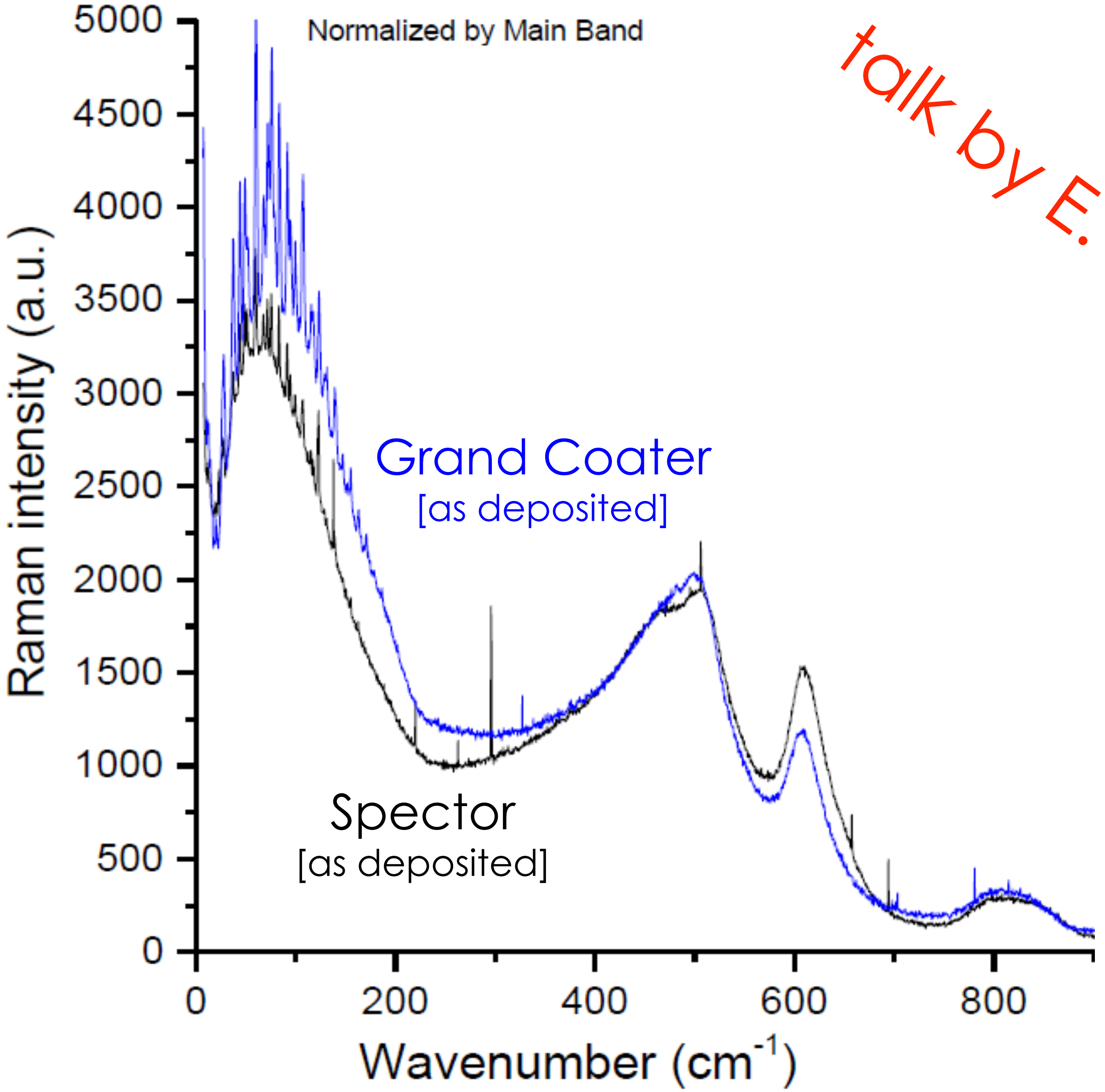


# deposition parameters and annealing
# - $SiO_2$ -

# deposition parameters

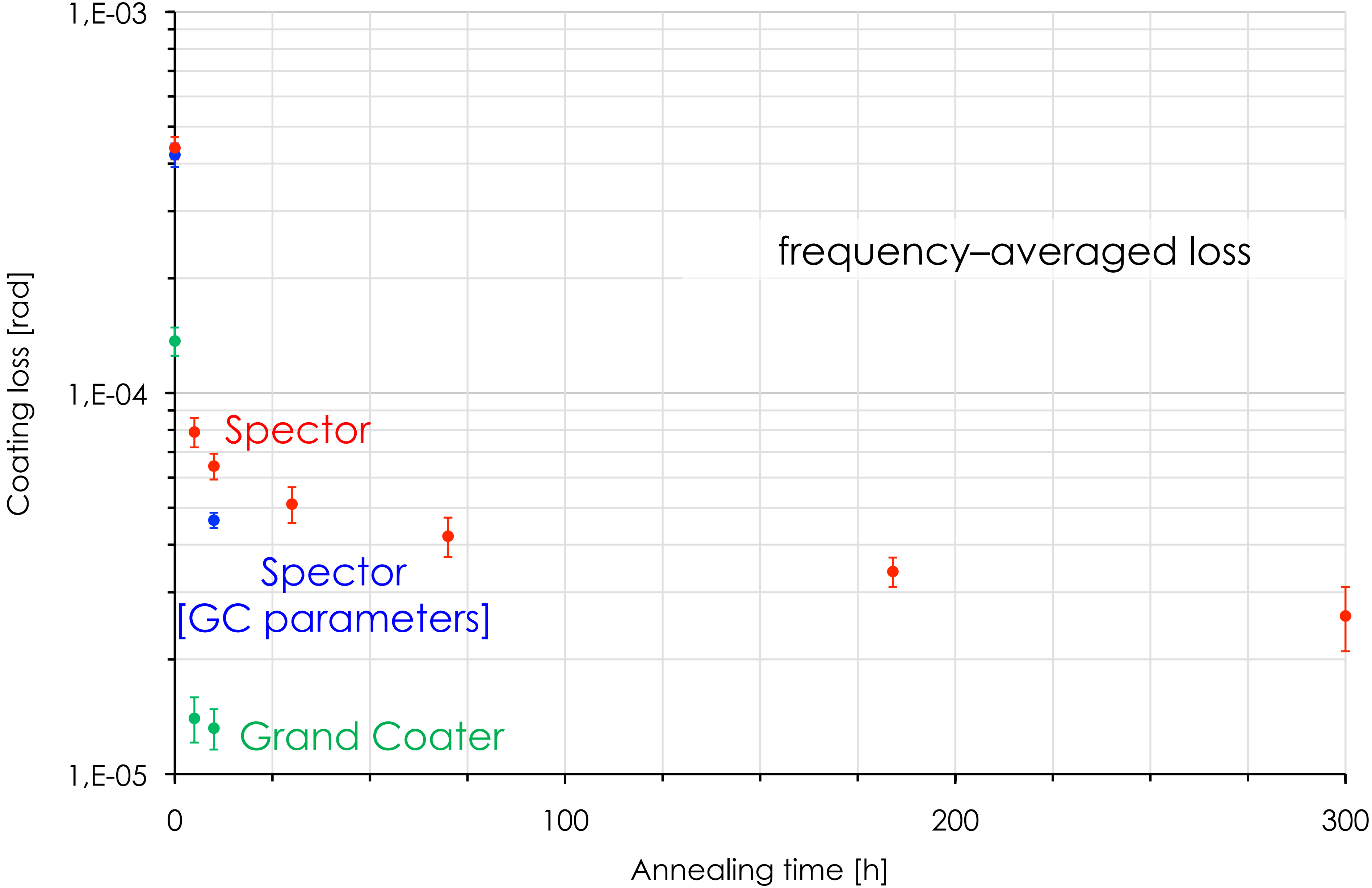


# structure



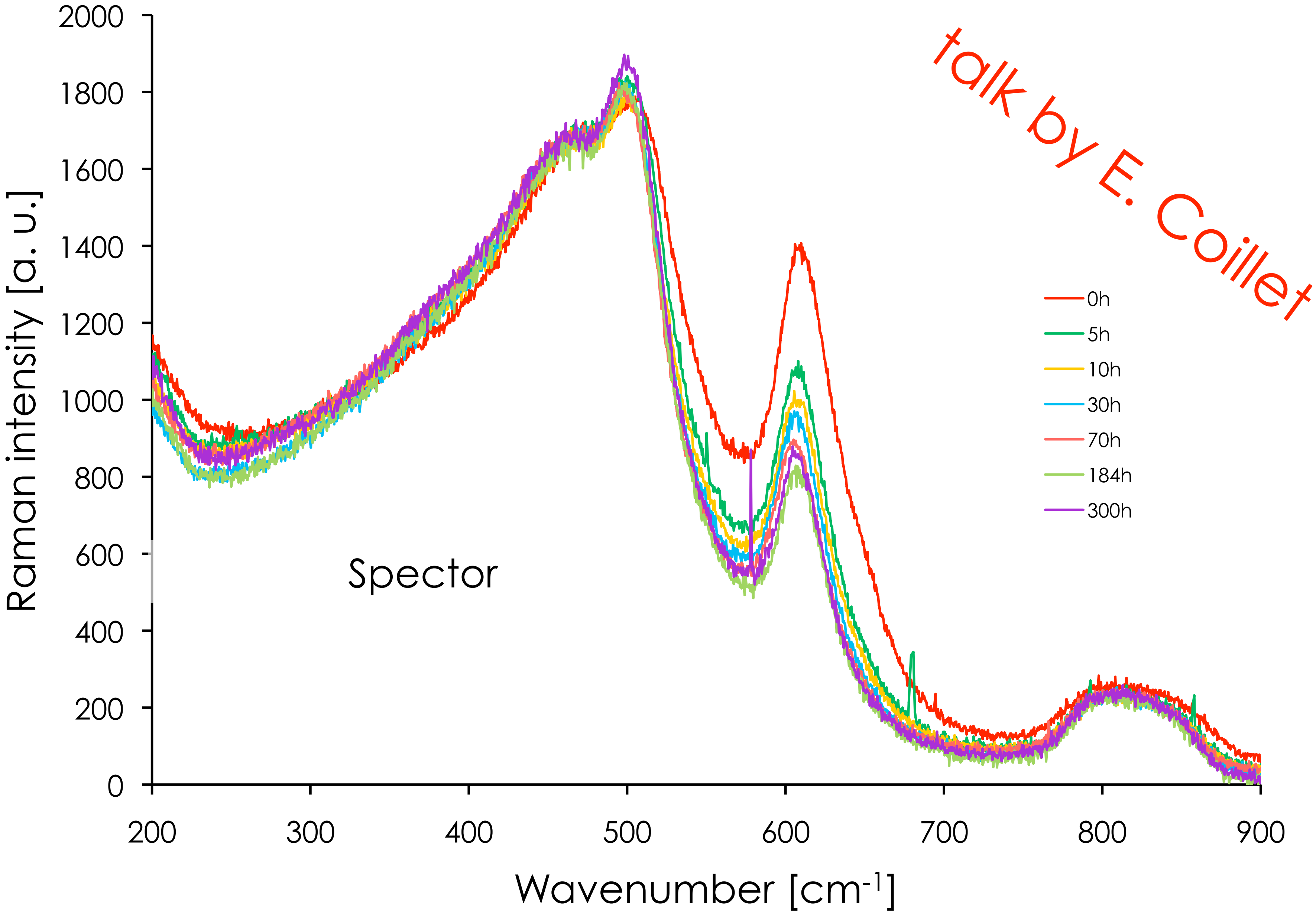

talk by E. Coillet

# annealing



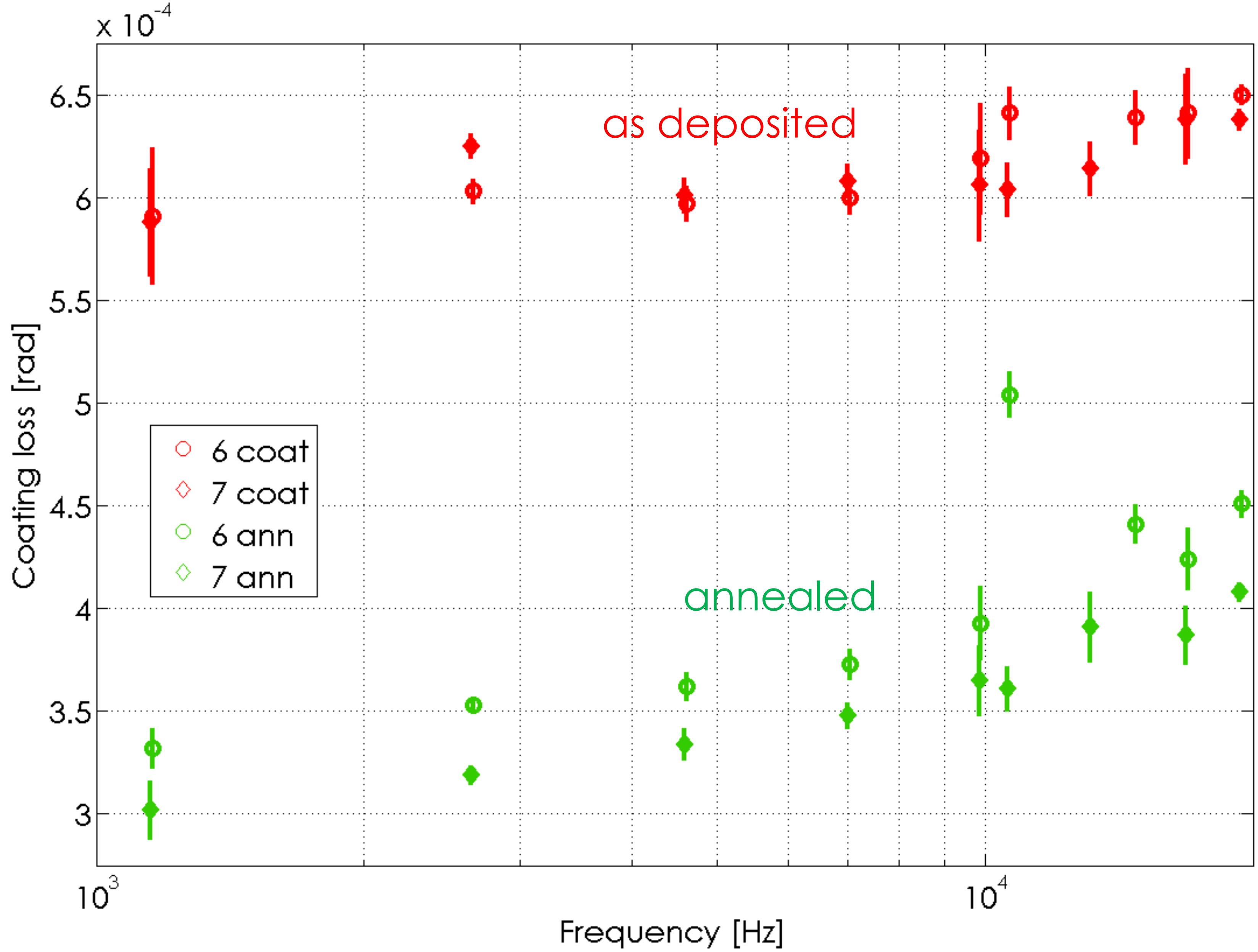
1,E-03
1,E-04
1,E-05
Coating loss [rad]
frequency–averaged loss
Spector
Spector
[GC parameters]
Grand Coater
0
100
200
300
Annealing time [h]

# structure


talk by E. Coillet
Raman intensity [a. u.]
Wavenumber [cm-1]
Spector
0h
5h
10h
30h
70h
184h
300h
2000
1800
1600
1400
1200
1000
800
600
400
200
0
200
300
400
500
600
700
800
900

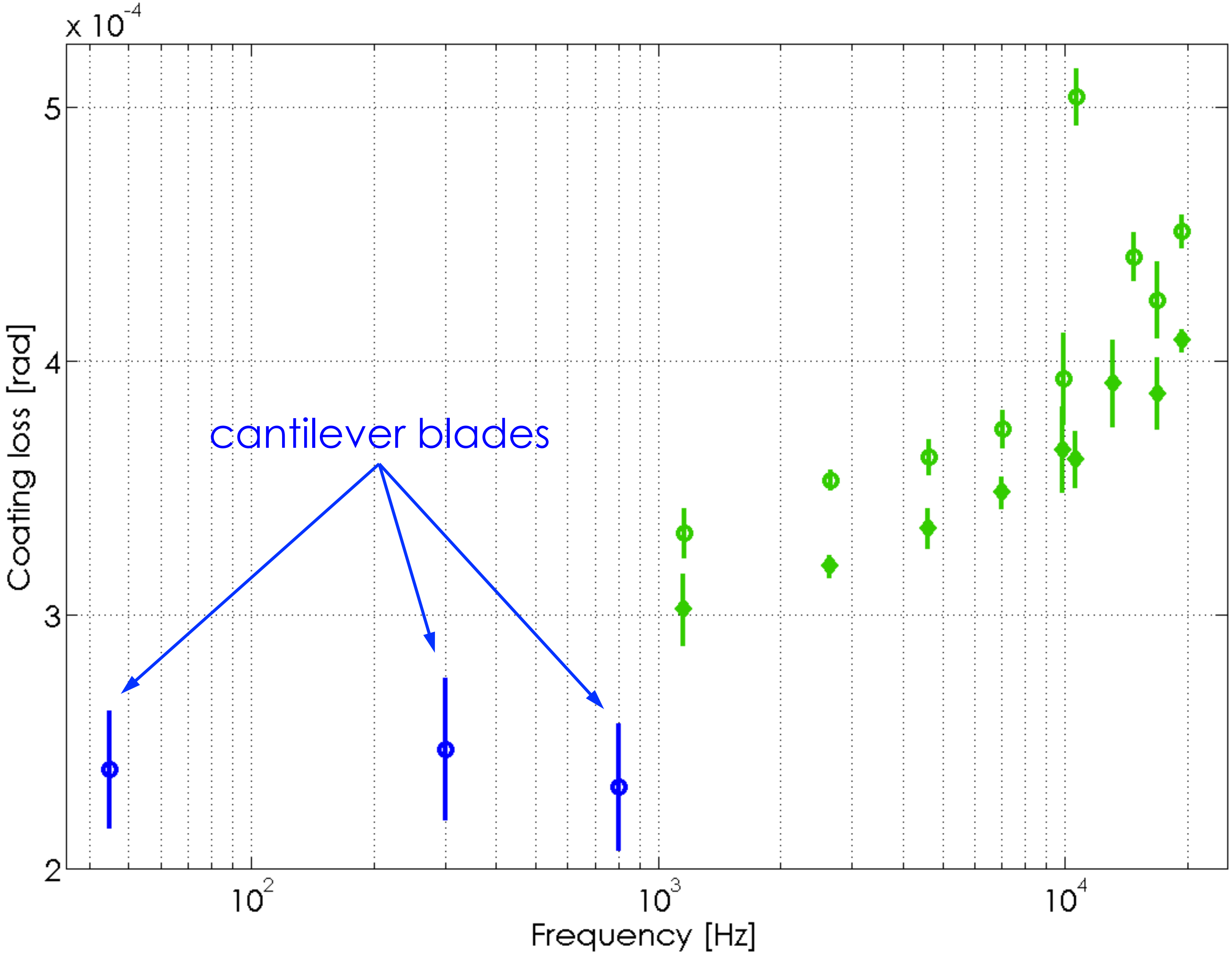
# advanced detectors' TiO2Ta2O5

# samples 6 & 7



x 10^-4
6.5
6
5.5
5
4.5
4
3.5
3
Coating loss [rad]
as deposited
annealed
6 coat
7 coat
6 ann
7 ann
10^3
10^4
Frequency [Hz]

# previous results – comparison



# coating loss [x$10^4$]

neglecting frequency dependence:

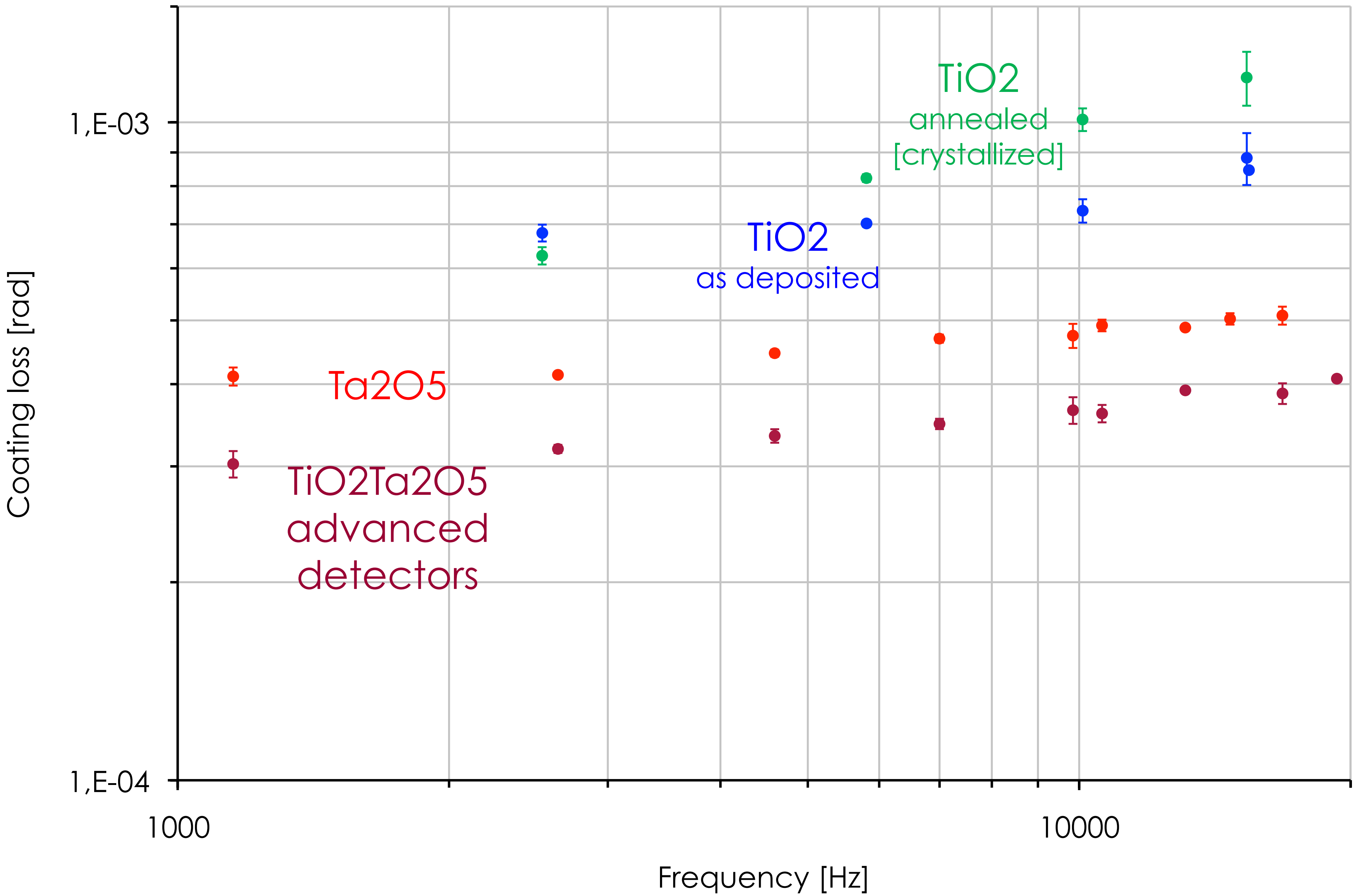
| | sample 6 | sample 7 |
|---|---|---|
| $\Phi_{asDep}$ | 6.2 ± 0.2 | 6.1 ± 0.2 |
| $\Phi_{ann}$ | 4.0 ± 0.6 | 3.6 ± 0.4 |

| | |
|---|---|
| Thermal-Noise Interferometer[1] | 3.66 ± 0.26 |
| cantilever blades[2] | 2.4 ± 0.3 |

[1] Principe & al, Phys. Rev. D 91, 022005 (2015)
[2] Granata & al, Phys. Rev. D 93, 012007 (2016)

*actual* impact of $TiO_2$ doping

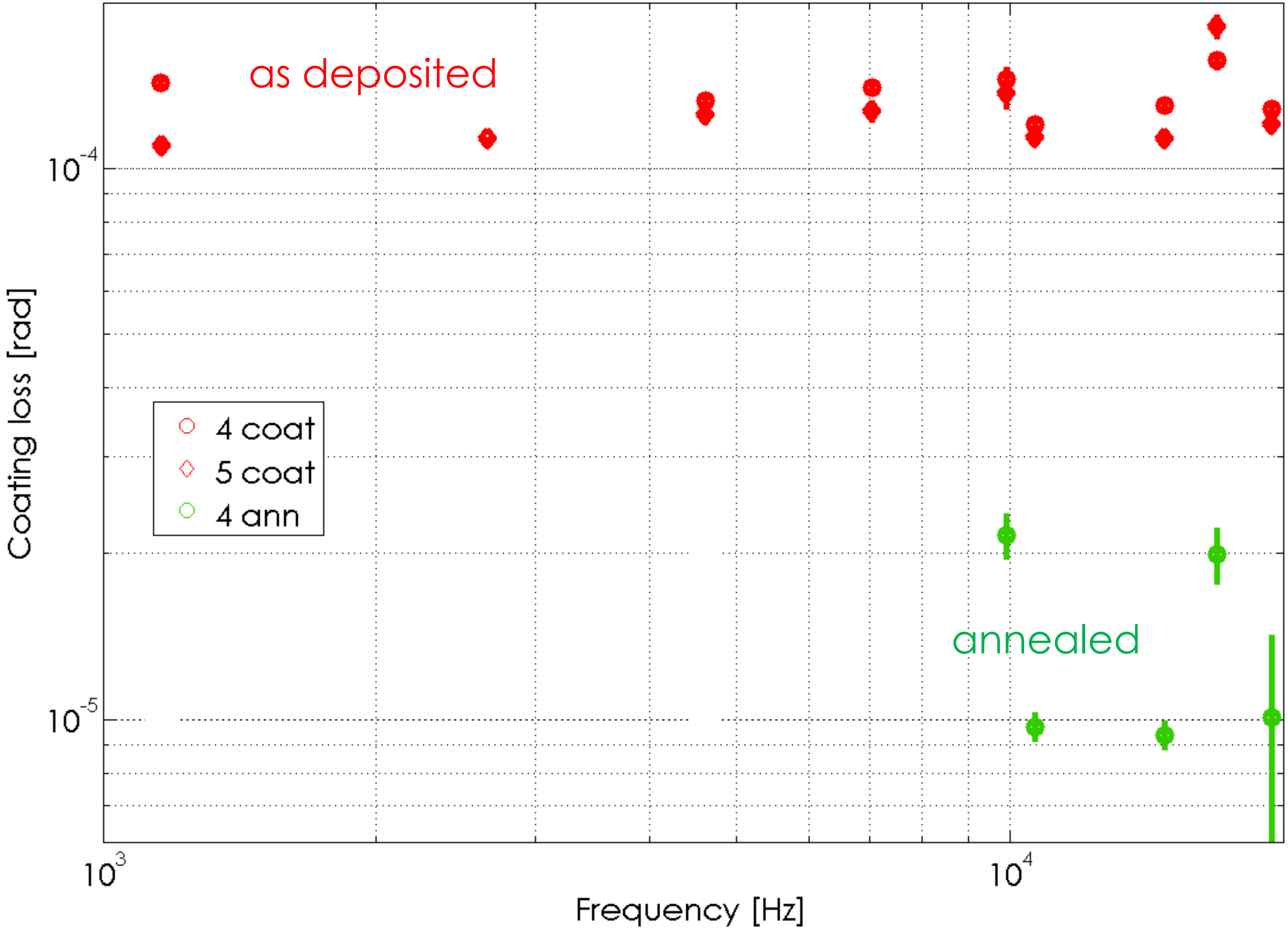
# TiO2 doping



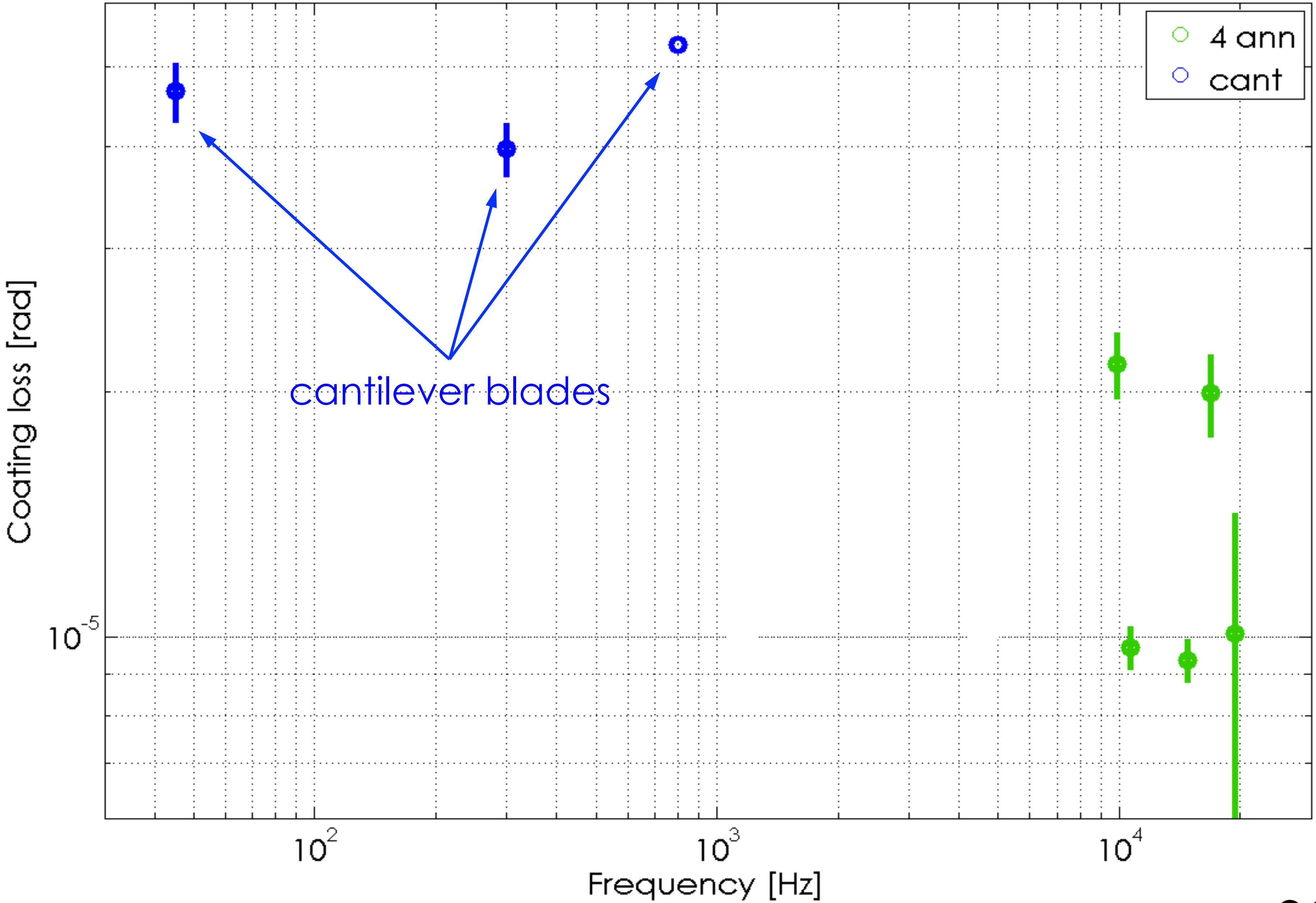
TiO2
annealed
[crystallized]
TiO2
as deposited
Ta2O5
TiO2Ta2O5
advanced
detectors
1,E-03
1,E-04
1000
10000
Coating loss [rad]
Frequency [Hz]

# advanced detectors' $SiO_2$

# samples 4 & 5


as deposited
annealed
4 coat
5 coat
4 ann
Coating loss [rad]
Frequency [Hz]
$10^{-4}$
$10^{-5}$
$10^{3}$
$10^{4}$

# previous results – comparison



# coating loss [x$10^4$]

neglecting shape dependence:

| | sample 4 | sample 5 |
|---|---|---|
| $\Phi_{asDep}$ | 1.4 ± 0.1 | 1.3 ± 0.2 |
| $\Phi_{ann}$ | 0.14 ± 0.06 | |

| | |
|---|---|
| fiber-suspended disks[1] | 0.5 ± 0.3 |
| Thermal-Noise Interferometer[2] | 0.51 ± 0.07 |
| cantilever blades[3] | 0.45 ± 0.03 |
| q-pITF[4] | 0.62 ± 0.48 |

[1] Penn & al, Class. Quantum Grav. 20 (2003)
[2] Principe & al, Phys. Rev. D 91, 022005 (2015)
[3] Granata & al, Phys. Rev. D 93, 012007 (2016)
[4] Li & al, Phys. Rev. D 89, 092004 (2014)

# HR coatings of advanced detectors

photo: C. Fresillon – photothèque CNRS

# model

optimized TiO2Ta2O5/SiO2 stacks

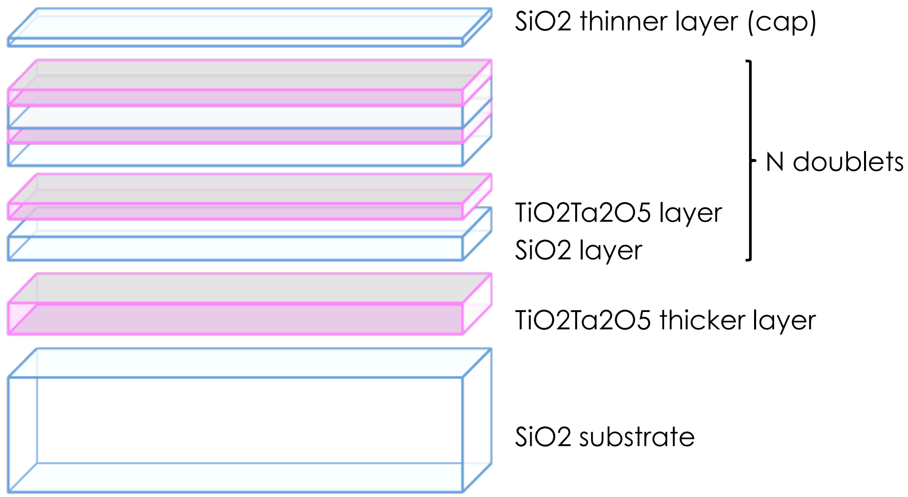
$N_{ITM} = 8$

$N_{ETM} = 18$

expected loss[1]:

$$\phi_{\mathrm{HR}} = \frac{\sum t_i Y_i \phi_i}{\sum t_i Y_i}$$

i = TiO2Ta2O5, SiO2

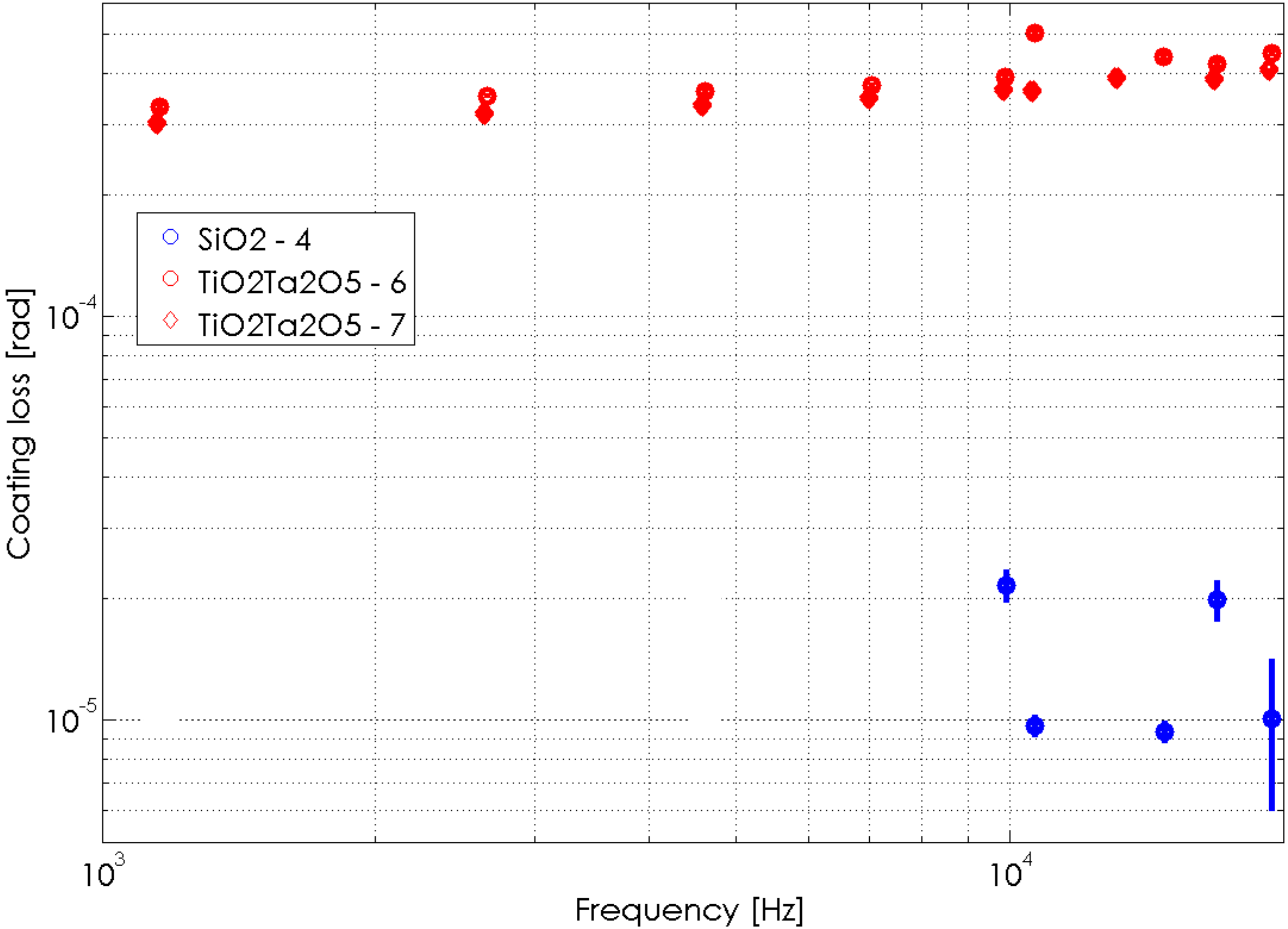



$Y_{TiO2Ta2O5} = 140$ GPa

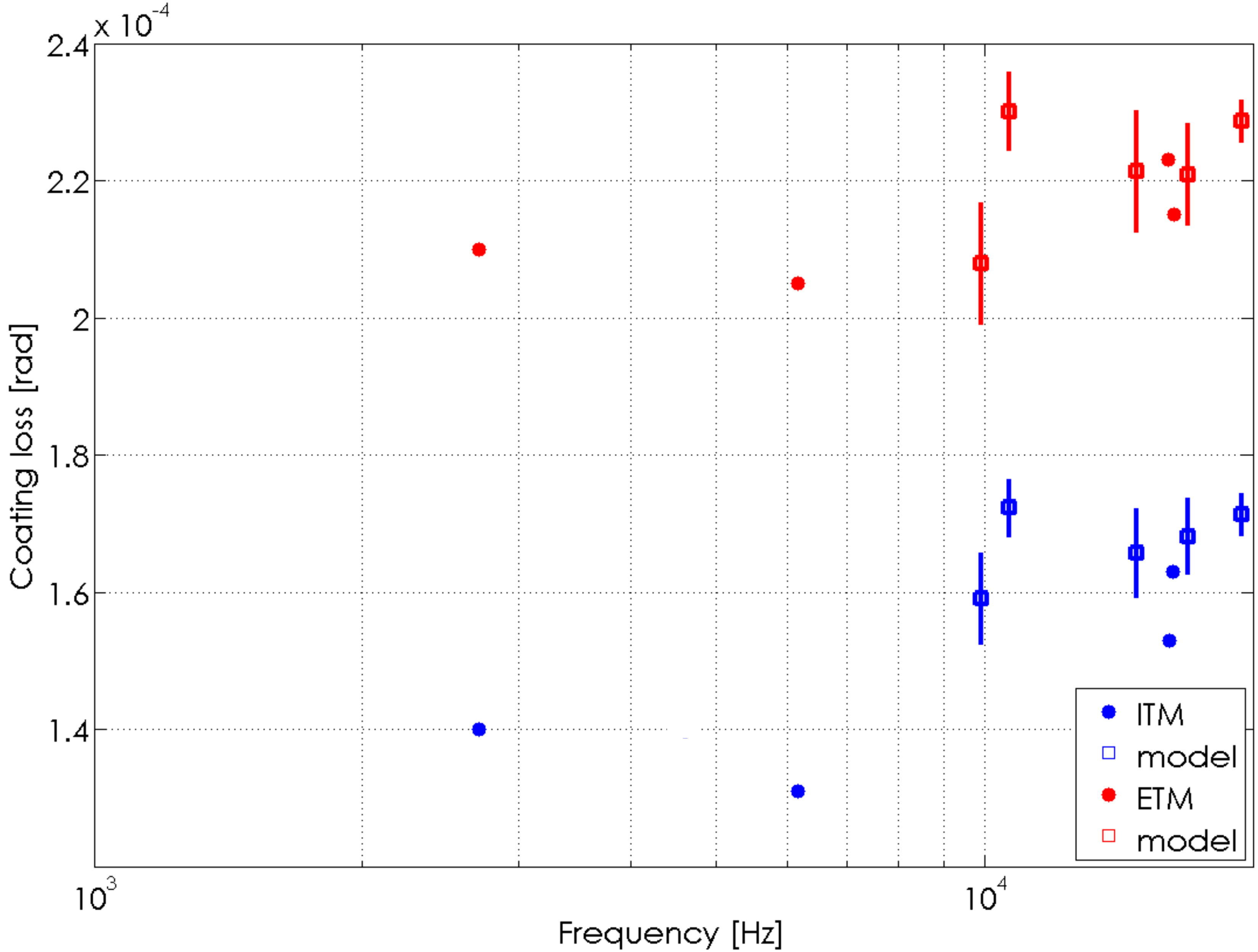
$Y_{SiO2} = 72.3$ GPa

[1] Penn & al, Class. Quantum Grav. 20 (2003)

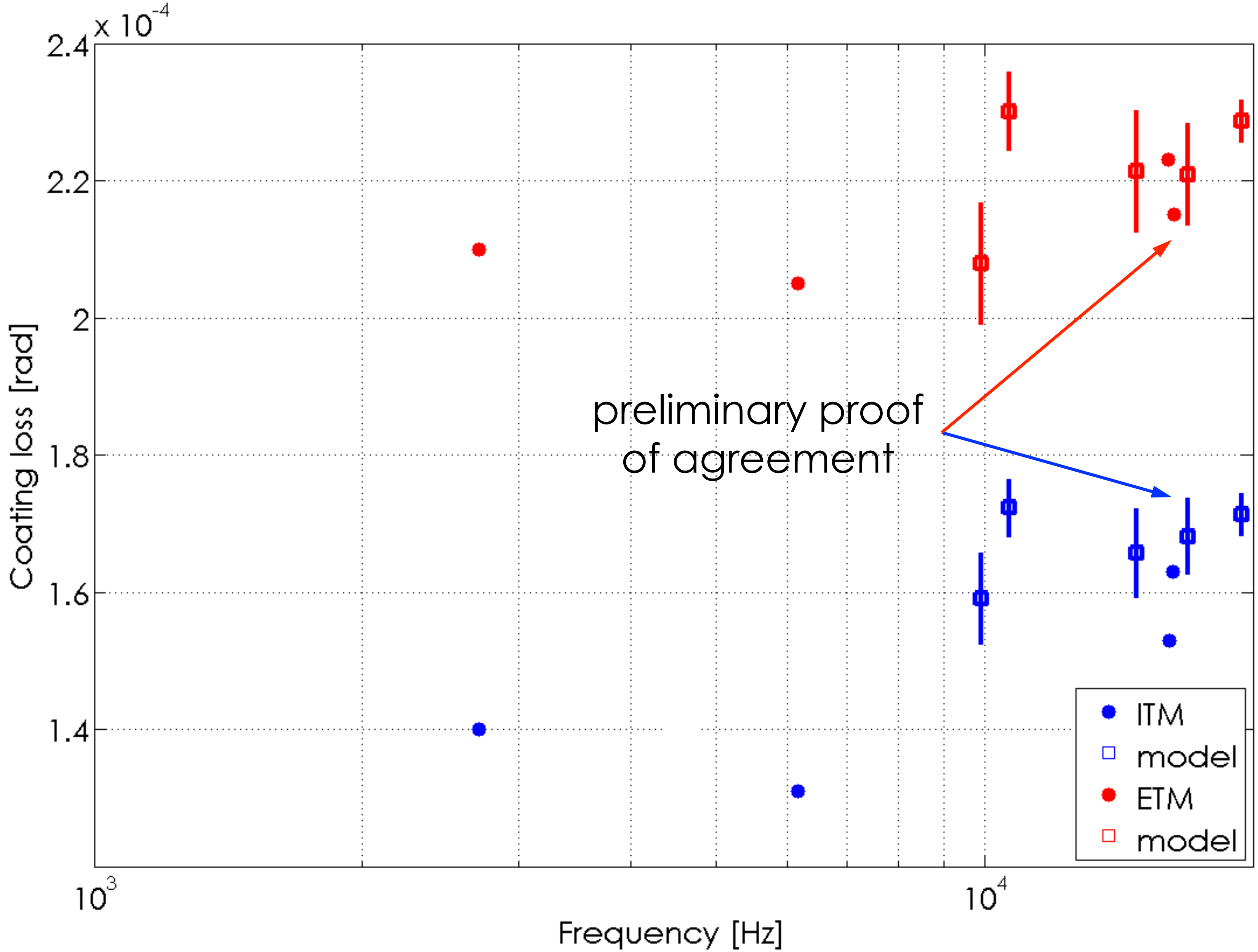
# monolayers


SiO2 - 4
TiO2Ta2O5 - 6
TiO2Ta2O5 - 7
Coating loss [rad]
10^-4
10^-5
10^3
10^4
Frequency [Hz]

# stack loss – theory & measurements



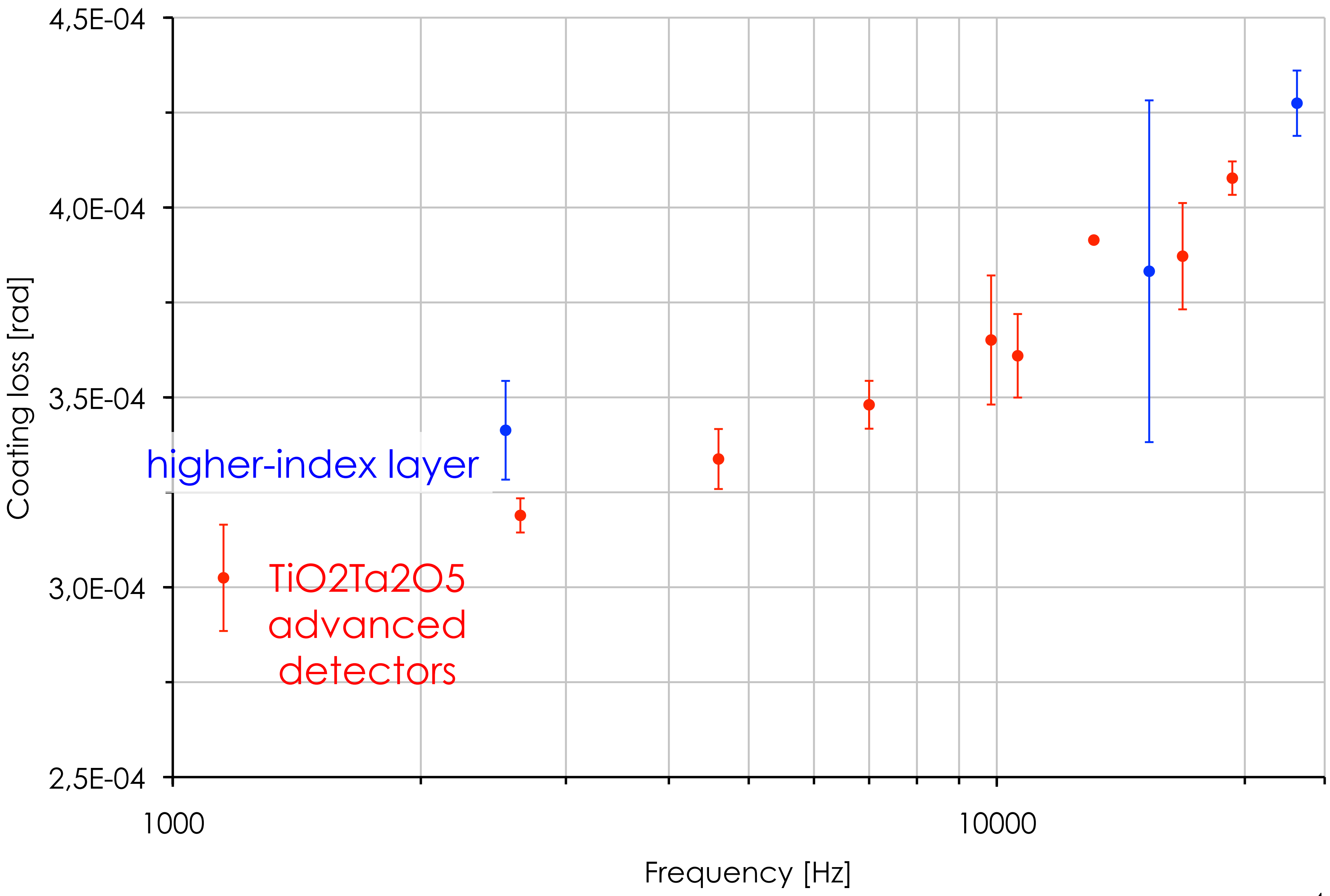
# stack loss – theory & measurements



PRELIMINARY

new higher-index layer

# comparison


4,5E-04
4,0E-04
3,5E-04
3,0E-04
2,5E-04
Coating loss [rad]
1000
10000
Frequency [Hz]
higher-index layer
TiO2Ta2O5
advanced
detectors

# improvement

| | $TiO_2Ta_2O_5$ | new high-index layer |
|---|---|---|
| $\Phi_{\sim 2.5\ kHz}$ | $(3.20 \pm 0.04) \cdot 10^{-4}$ | $(3.41 \pm 0.13) \cdot 10^{-4}$ |
| $\Phi_{\sim 14\ kHz}$ | $3.9 \cdot 10^{-4}$ | $(3.8 \pm 0.5) \cdot 10^{-4}$ |
| $n_{1064\ nm}$ | $2.050 \pm 0.005$ | $2.095$ |

➡ similar loss

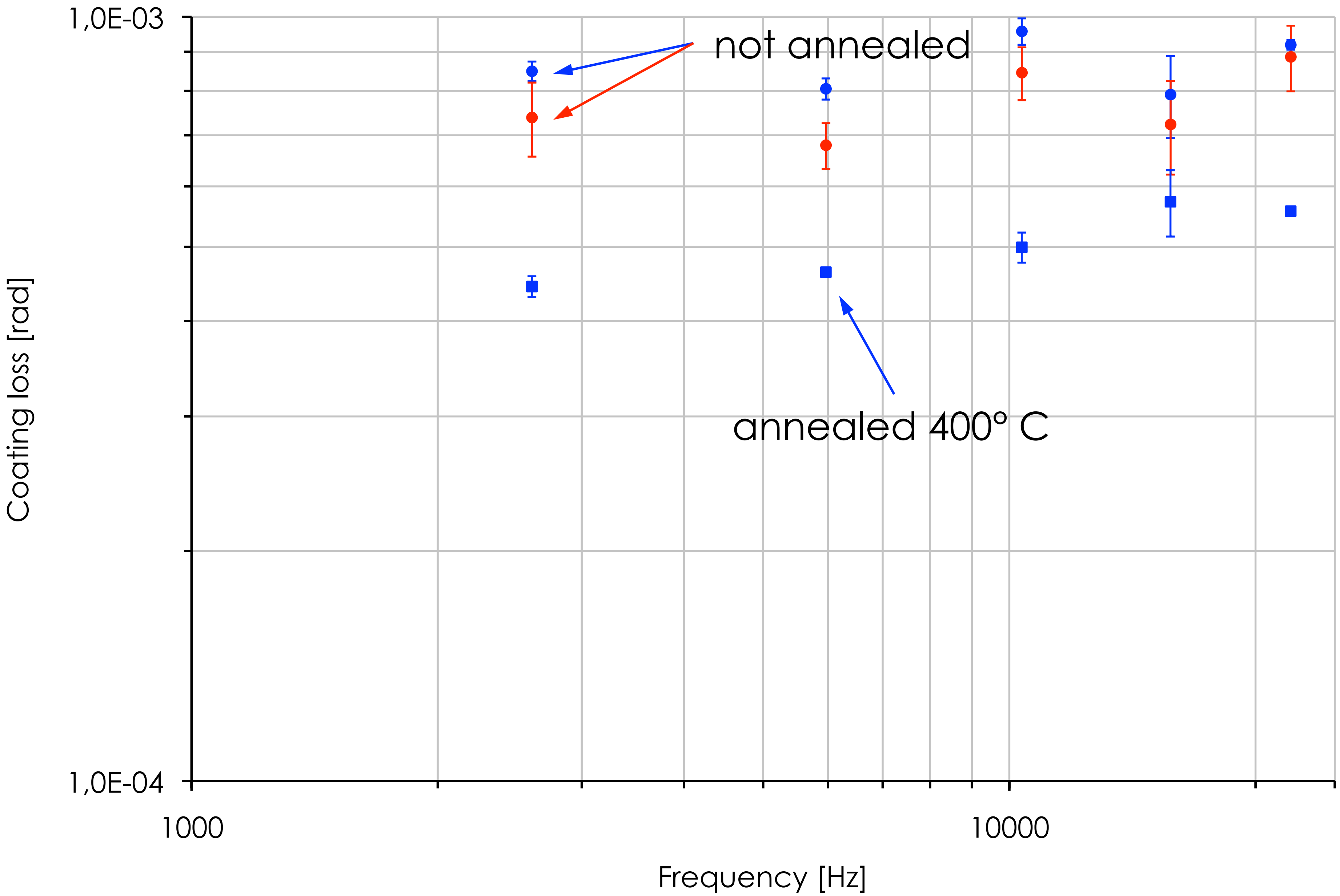
higher index ➡ thinner layers ➡ 6% thinner ETM stack [-1 doublet]

lower stack loss expected

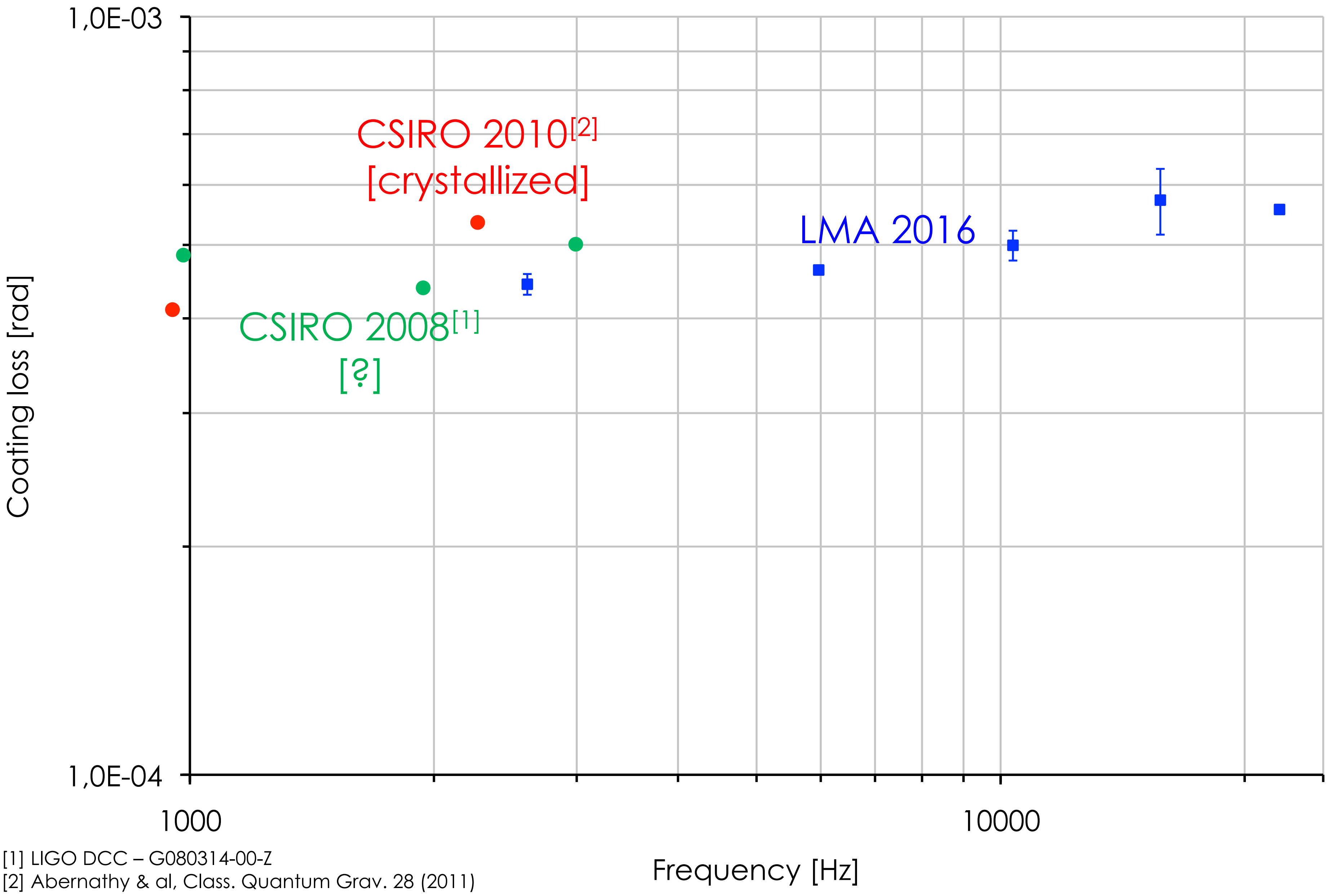
PRELIMINARY

# HfO2 for cryogenic detectors

# HfO2 – Spector



# comparison




[1] LIGO DCC – G080314-00-Z
[2] Abernathy & al, Class. Quantum Grav. 28 (2011)

# characterization

optical absorption / scattering measurements ongoing

preliminary results → amorphous material

X-ray diffraction measurements ongoing

as deposited / 300° C- / 400° C-annealed monolayers

# summary & conclusions

# coating loss

dilution factor can be measured

# coating loss

dilution factor can be measured

loss depends on

coating deposition parameters

post-deposition history

→ shared protocol needed to validate/compare measurements

# coating loss

dilution factor can be measured

loss depends on

- coating deposition parameters
- post-deposition history

→ shared protocol needed to validate/compare measurements

advanced detectors' materials

- new characterization completed
- doping impact revised
- preliminary proof of HR stacks' loss model

# coating loss

new amorphous materials

new higher-index layer

$HfO_2$ – reconsidered for cryogenic detectors

work ongoing

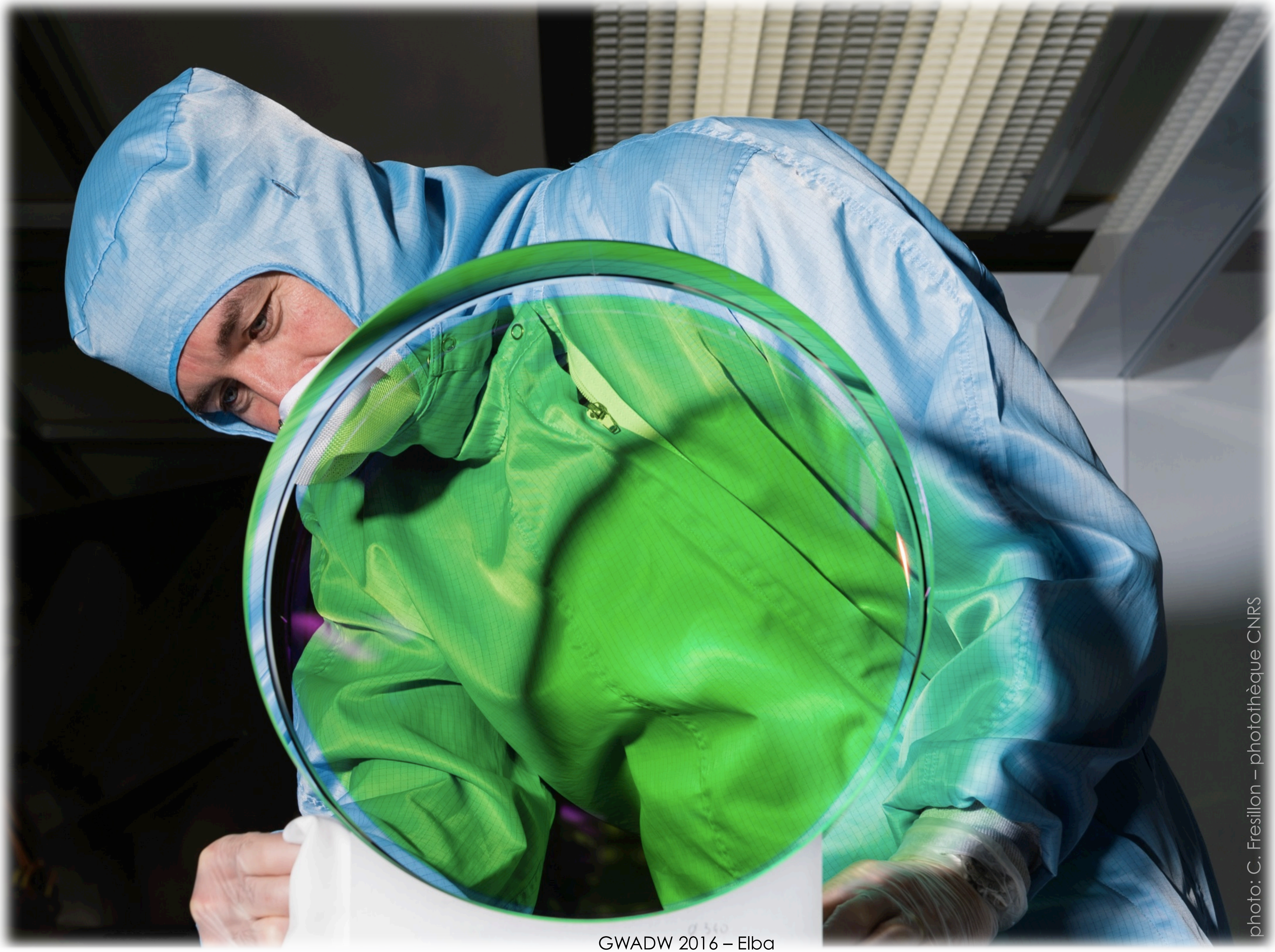
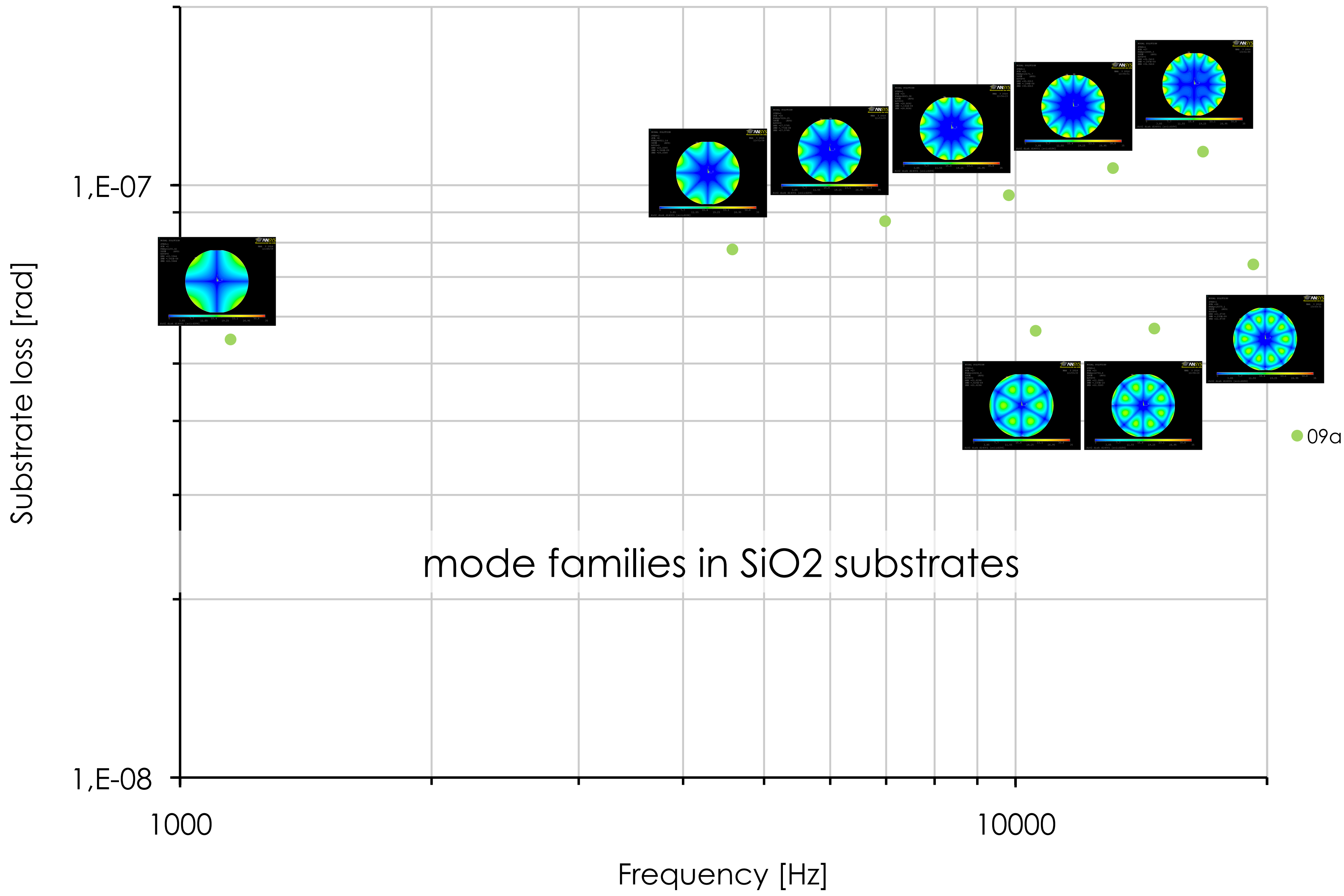


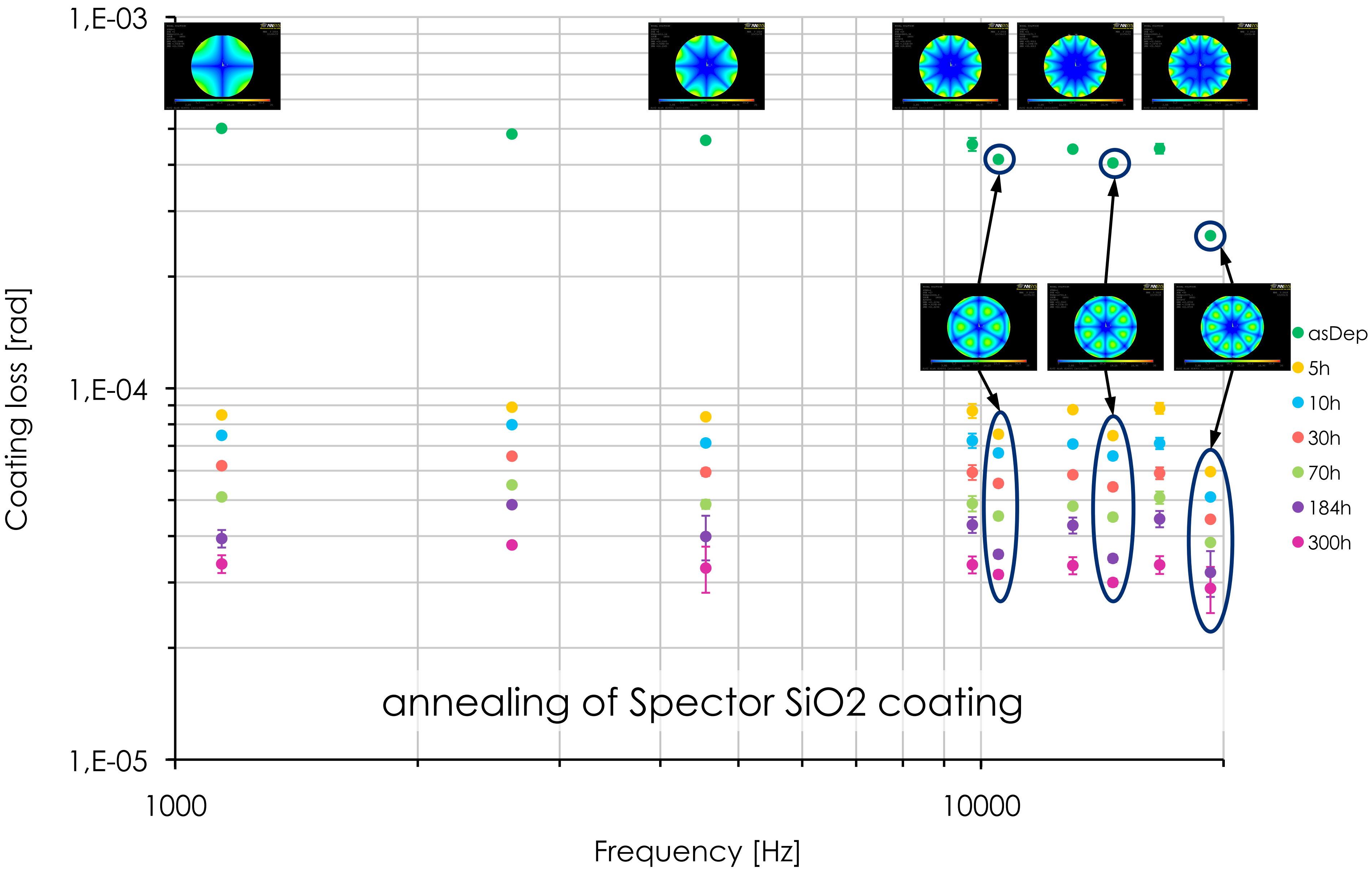
photo: C. Fresillon – photothèque CNRS

# sample 9



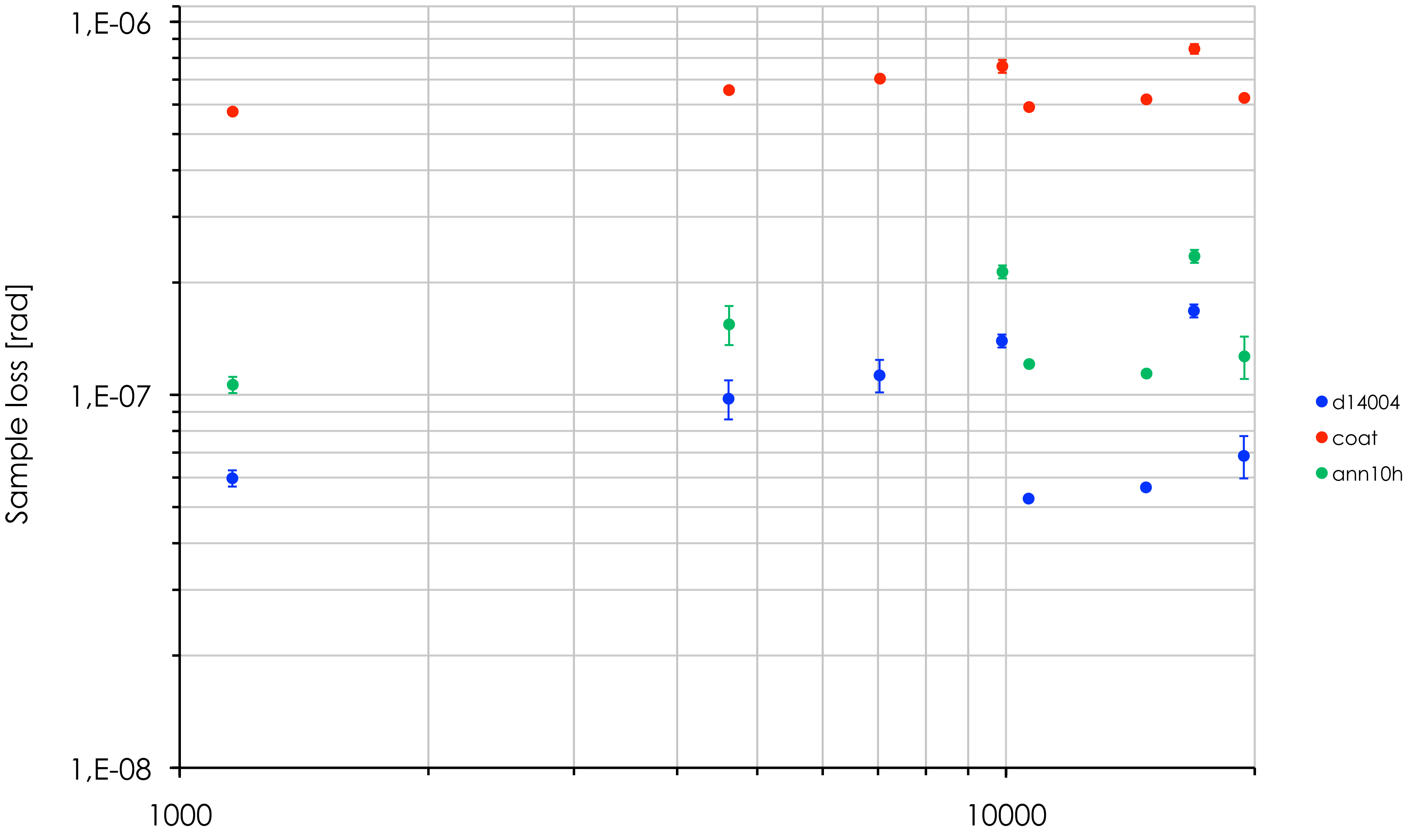
1,E-07
1,E-08
Substrate loss [rad]
1000
10000
Frequency [Hz]
09a
mode families in SiO2 substrates

# sample 2



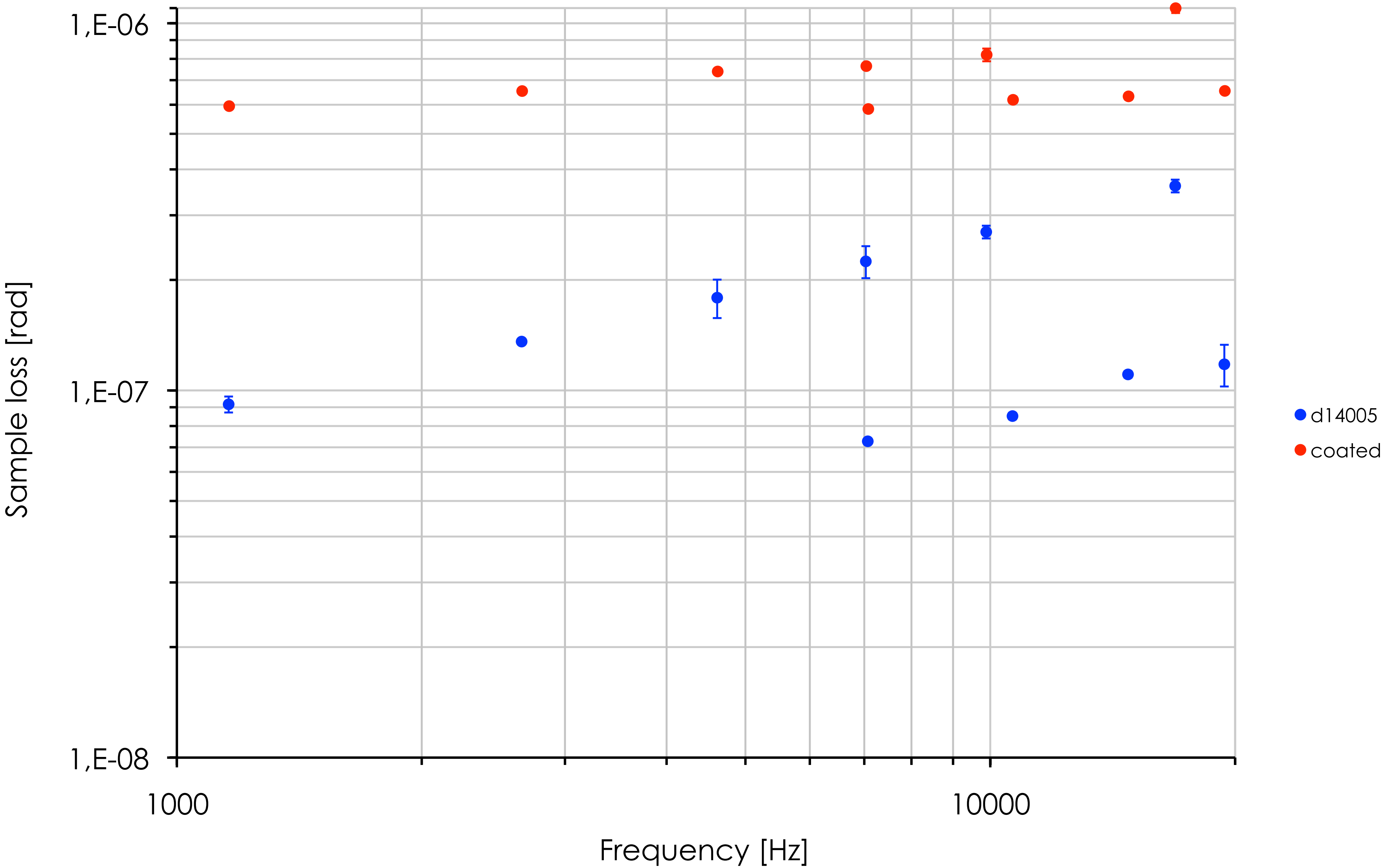
1,E-03
1,E-04
1,E-05
Coating loss [rad]
1000
10000
Frequency [Hz]
asDep
5h
10h
30h
70h
184h
300h
annealing of Spector SiO2 coating

# sample 4

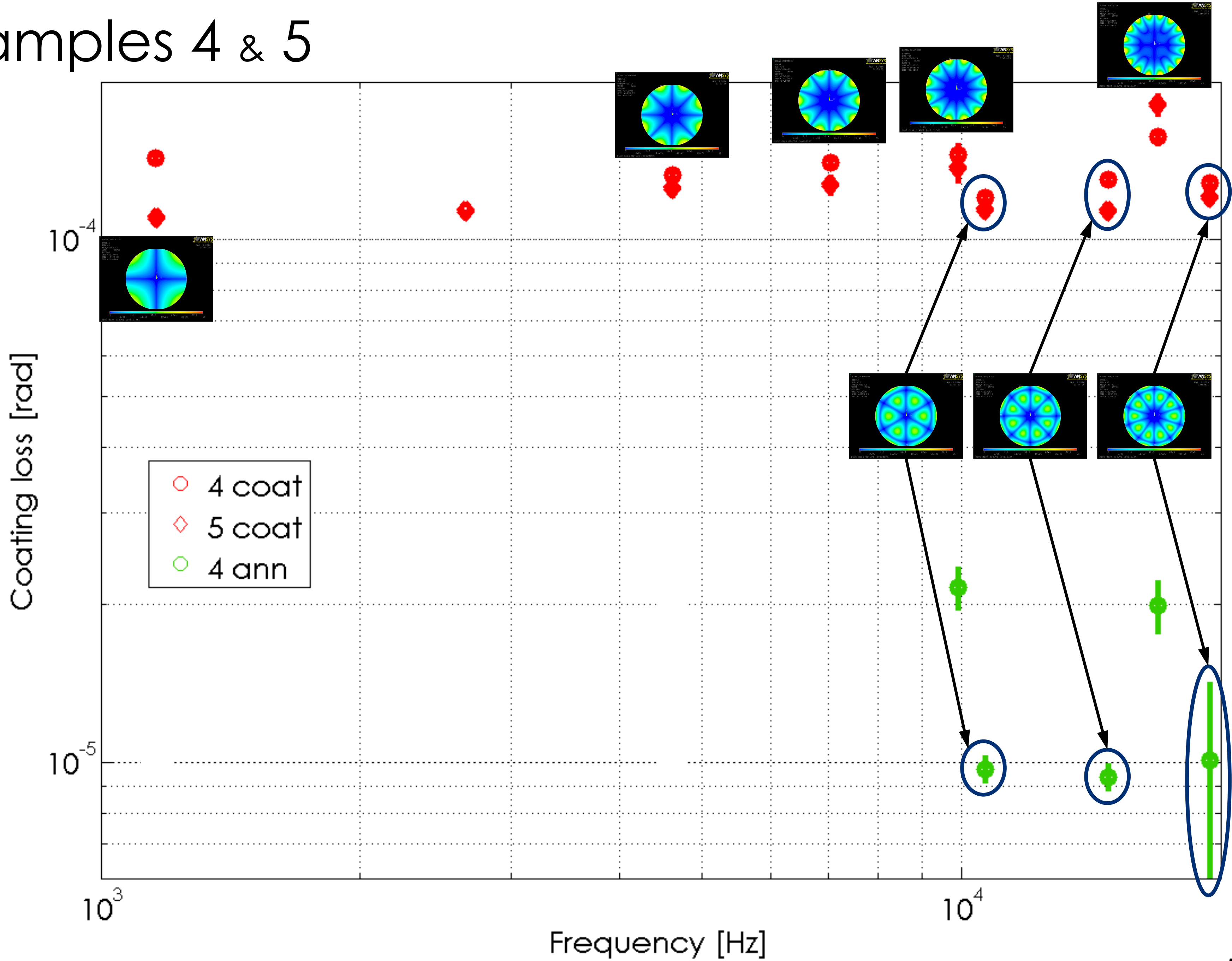


1,E-06
1,E-07
1,E-08
1000
10000
Frequency [Hz]
Sample loss [rad]
d14004
coat
ann10h

# sample 5

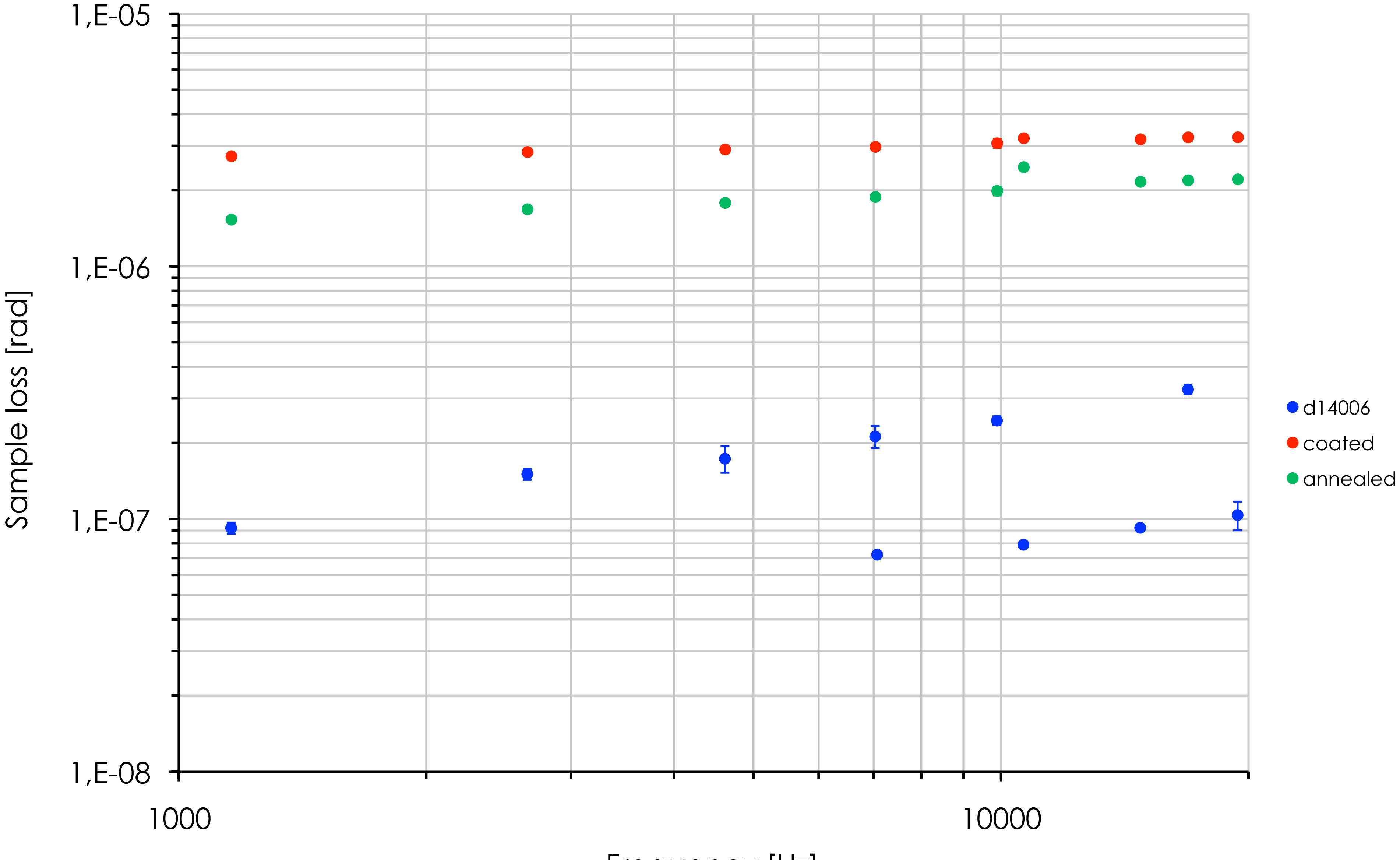

1,E-06
1,E-07
1,E-08
Sample loss [rad]
1000
10000
Frequency [Hz]
d14005
coated

# samples 4 & 5

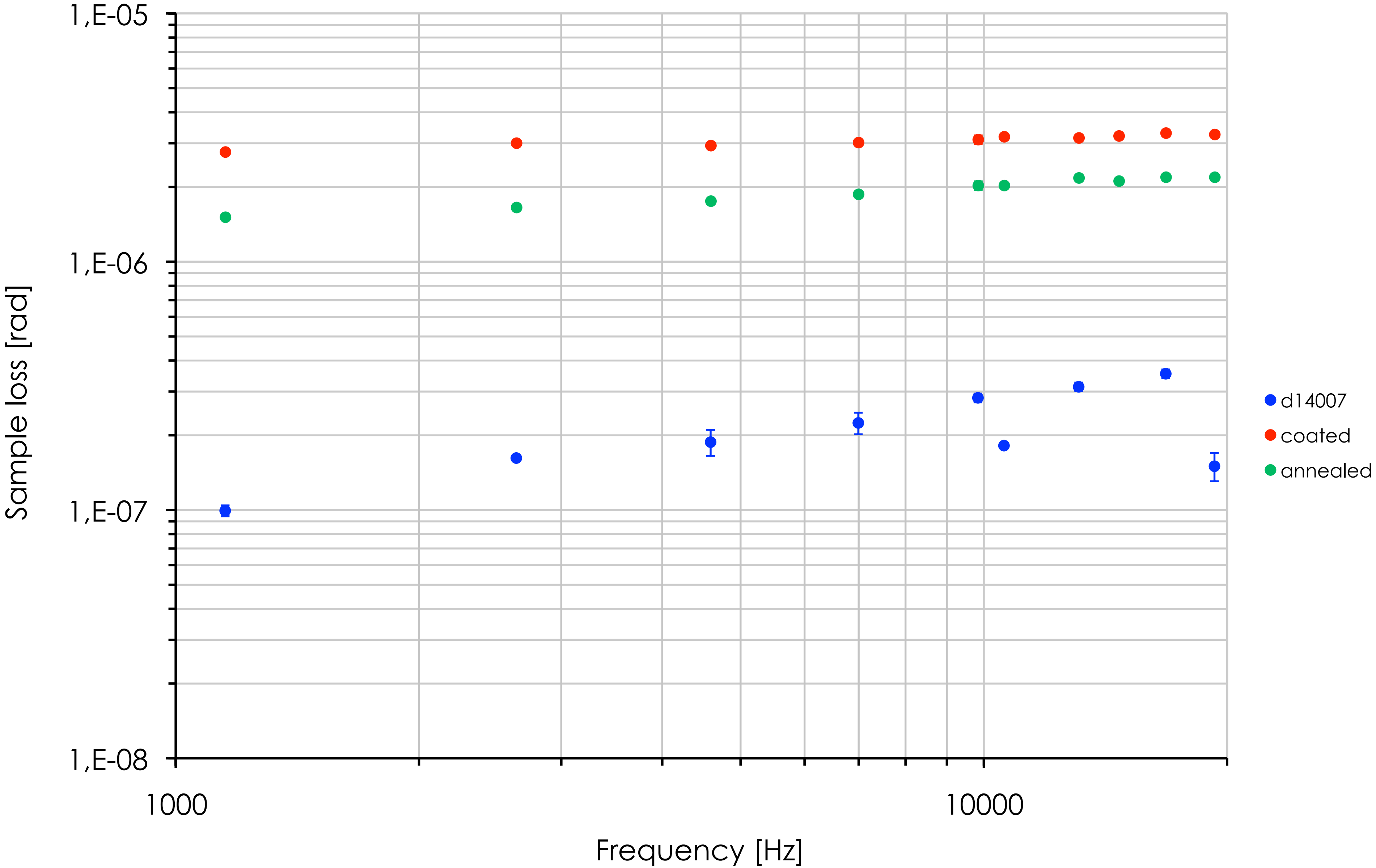


Coating loss [rad]
$10^{-4}$
$10^{-5}$
$10^{3}$
$10^{4}$
Frequency [Hz]
4 coat
5 coat
4 ann

# sample 6


1,E-05
1,E-06
1,E-07
1,E-08
Sample loss [rad]
1000
10000
Frequency [Hz]
d14006
coated
annealed

# sample 7



1,E-05
1,E-06
1,E-07
1,E-08
Sample loss [rad]
1000
10000
Frequency [Hz]
d14007
coated
annealed